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Airspace analysis for greener operations: towards more adoptability and predictability of continuous descent approach (cda)

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ABSTRACT

AIRSPACE ANALYSIS FOR GREENER OPERATIONS: TOWARDS MORE ADOPTABILITY AND PREDICTABILITY OF CONTINUOUS DESCENT APPROACH (CDA)

by
Emad Ali Alharbi

Continuous Descent Approach (CDA), also known as Optimized Profile Descent (OPD), is the advanced flight technique for commercial aircraft to descend continuously from cruise altitude to Final Approach Fix (FAF) or touchdown without level-offs and with- or near-idle thrust setting. Descending using CDA, aircraft stays as high as possible for longer time thereby expanding the vertical distance between aircraft's sources of noise and ground, and thus significantly reducing the noise levels for populated areas around airports. Also, descending with idle engines, fuel burn is reduced resulting in reduction of harmful emissions to the environment and fuel consumption to air carriers. Due to safety considerations, CDA procedures may require more separation between aircraft, which could reduce the full utilization of runway capacity. Thus, CDA has been limited to low to moderate traffic levels at airports. Several studies in literature have used various approaches to present solutions to the problem of increasing the CDA implementation during periods of high traffic at airports. However, insufficient attention was given to define thresholds that would help Air Traffic Controllers (ATC) to manage and accommodate more CDA operations, strategically and tactically. Bridging this gap is the main intent of this work.

This research focus is on increasing CDA operations at airports during high traffic levels by considering factors that impact its CDA adoption as they relate to airports' demographics, and airspace around them {known as terminal maneuvering area (TMA)}. To capture the effect of these factors on CDA Adoptability (CDA-A), in general, and CDA Predictability (CDA-P), at the operational level, two (2) approaches are introduced. The CDA-A model defines and captures the maximum level of traffic threshold for CDA adoption. The model captures the factors affecting CDA in a single measure, which are designated collectively as the Probability of Blocking. It is defined as the fraction of time an aircraft's request to embark on CDA is denied. The denial could emanate from safety concerns as well as other operational conditions, such as the congestion of the stacking space within the TMA. This metric should enhance ATC on the strategic level to increasing CDA operations during possibly higher traffic than normally the case. The other approach is for a CDA-P. This model is developed based on data-driven system approach. It extracts traffic features, such as aircraft type and speed, altitude, and rate of descent; from actual flights data to aid in further operational utilization of CDA in real time. By accurately predicting CDA instances during high traffic at airports, the CDA-P model should assist ATC manage adopting more CDA operations during periods of high demand. Through its framework, the CDA-P model utilizes Feature Engineering and Hierarchal Clustering Analysis, to facilitate descent profile visualization and labeling, for building, training, testing, and validation of CDA predictive models using Decision Trees with AdaBoost and Support Vector Machines (SVM). The CDA-P model is validated using actual flight data operated at Nashville Int'l Airport (BNA).

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AIRSPACE ANALYSIS FOR GREENER OPERATIONS: TOWARDS MORE ADOPTABILITY AND PREDICTABILITY OF CONTINUOUS DESCENT APPROACH (CDA)

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هذه الرسالة مُهداة إلى روح والدي الحبيب؛
علي أحمد آل فرحان المورعي الحربي
إلى والدتي، أخواني، وأخواتي
إلى والد زوجتي ووالدة زوجتي
وإلى زوجتي، أروى، وأبنائي؛ همّام، لتين، بتيل، وعزّام
" أحبكُم جميعاً "

This dissertation is dedicated to the soul of my dearly beloved father;
Ali Ahmed Alharbi
to my mother, my brothers, and my sisters,
to my parents in law,
to my wife; *Arwa*, and my children; *Hammam*, *Lateen*, *Bateel*, and *Azzam*
"Love you All"

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LIST OF SYMBOLS

AAR	Airport Arrival Rate
V_{app}	Aircraft's approach speed (knots)
V_{TAS}	Aircraft true speed, in knots
V_{ground}	Aircraft ground speed, in feet per minute (*ft/min*)
g	Acceleration due to Earth gravity, in meter per second squared (m/s^2)
a_o	Speed of sound at mean sea level, in meter per second (*m/s*)
M_{cruise}	Aircraft Mach at cruise (*dimensionless*)
T	Air temperature at altitude, in Kelvin (K)
T_o	Air temperature at mean sea level, in Kelvin (K)
ρ	Density of air, in kilograms per meter cubed (kg/m^3)
ρ_l	Traffic intensity
k	Number of aircraft stacked for approach
S	Aircraft wing area, in meter squared (m^2)
S_p	Space available to stack aircraft arrivals at airport (*nmi*)
L	Lift force, in Newton (N)
d	Minimum allowable horizontal separation distance between a pair of same-weight-class aircraft (*nmi*)
d_{CDA}	Separation distance between pair of aircraft with CDA (*nmi*)
$d_{Non-CDA}$	Separation distance between pair of aircraft without CDA (*nmi*)
D	Drag force, in Newton (N)

DD	Distance to Descent (*nmi*)
D_{des}	Distance aircraft covers during descent from TOD to touchdown (*nmi*)
$CDA-A$	Continuous Descent Approach Adaptability
$CDA-AF$	Continuous Descent Approach Adaptability Factor
$CDA-P$	Continuous Descent Approach Predictability
CA	Current altitude for aircraft (*ft*)
C_L	Lift coefficient (*dimensionless*)
C_D	Drag coefficient (*dimensionless*)
C_{D_o}	Zero-lift drag coefficient (*dimensionless*)
C_{D_i}	Induced drag coefficient (*dimensionless*)
m	Aircraft weight, in kilograms (*kg*)
γ	Flight path angle (*degrees*)
NA	New altitude for aircraft (*ft*)
t_{des}	Time aircraft takes to descent from TOD to touchdown (*minutes*)
$Thr_{\text{max,climb}}$	Maximum aircraft's thrust at climb, in Newton (N) [BADA]
Thr_{des}	Aircraft's thrust at descent, in Newton (N) [BADA]
$Thr_{\text{des,low}}$	Aircraft's descent thrust for cruise configuration, in Newton (N) [BADA]
$Thr_{\text{des,app}}$	Aircraft's descent thrust for approach configuration, in Newton (N) [BADA]
$Thr_{\text{des,ld}}$	Aircraft's descent thrust for landing configuration, in Newton (N) [BADA]
TOD	Top of Descent

H_p	Geopotential pressure altitude, in feet (*ft*) [BADA}
h	Geodetic altitude, in feet (*ft*) [BADA]
h_f	Final approach fix altitude, in feet (*ft*)
Δh	Altitude difference that aircraft needs to dissipate during descent (*ft*)
ROD	Aircraft's rate of descent, in feet per minute (*ft/min*) [BADA]
W_s	Wind speed (*mph*)
λ_s	Average demand rate of Terminal Maneuvering Area at airport
λ_{CDA}	Average arrival rate of CDA operations (CDA operation/hour)
μ	Absolute viscosity coefficient of air (dimensionless)
μ_s	Average service rate of Terminal Maneuvering Area at airport
P_k	Probability of Blocking
$P_{k_{CDA}}$	Probability of Blocking for CDA operations
$P_{k_{SDA}}$	Probability of Blocking for SDA operations

LIST OF DEFINITIONS

Air Route Traffic Control Center	An air traffic control facility primarily responsible for ATC services being provided IFR aircraft during the en route phase of flight [ICAO].
Air Traffic Control	Service provided for the safe and efficient of air traffic.
Air Traffic Controller	Person whose job is to ensure correct separation of aircraft in all phases of flight.
Air Traffic Management	The dynamic, integrated management of air traffic and airspace including air traffic services, airspace management and air traffic flow management; safely, economically and efficiently, thorough the provision of facilities and seamless services in collaboration with all parties [ICAO].
Airport Arrival Rate	A dynamic input parameter specifying the number of arriving aircraft which an airport or airspace can accept per hour [FAA].
Airspace	Part of the atmosphere above the surface, subject to the laws of a particular country or controlling authority.
Area Navigation	A method of navigation which permits aircraft operation on any desired flight path within the coverage of ground- or space-based navigation aids or within the limits of the capability of self-contained aids, or a combination of both [FAA].
Descent	Loss of aircraft's altitude, usually in a planned maneuver, in preparation for landing.
Dive	To put the aircraft into a steep, nose-down attitude.
Drag	The resistance force of air created by moving the aircraft through the air.
Final Approach	Flight path in direction of landing along extended runway centerline.

Final Approach Fix	The fix from which the final approach to an airport is executed and which identifies the beginning of the final approach segment for an aircraft flies using instrument flight rules [FAA].
Final Approach Segment	That segment of an instrument approach procedure in which alignment and descent for landing are accomplished [ICAO].
Fix	A geographical position determined by visual reference to the surface, by reference to one or more radio navigational aids, by celestial plotting, or by another navigational devices [FAA].
Holding Fix Point	A position where aircraft wait before entering the runway, as instructed by air traffic controller (ATC).
Instrument Approach Procedure	A series of predetermined maneuvers for the orderly transfer of an aircraft from the beginning of the initial approach to landing or to a point from which a landing may be made visually [FAA].
Instrument Flight Rules	Rules governing the procedures for conducting instrument flight [FAA].
Optimized Profile Descents	Published arrival procedures designed with altitude restrictions to accommodate various aircraft types over a range of expected weather conditions.
Precision Approach Procedure	A standard instrument approach procedure in which an electronic glideslope/or other type of glide path is provided, (e.g., Instrument Landing System) [FAA].
Separation	The spacing of aircraft to achieve their safe and orderly movement in flight and while landing and taking off [FAA].
Straight-in Approach	An instrument approach wherein final approach is begun without first having executed a procedure turn, not necessarily completed with a straight-in landing or made a straight-in landing minimums [FAA].
Tailored Arrivals	Aircraft-specific trajectories generated by advanced ATM automation.
Threshold	Beginning of the part of the runway usable for landing.

Touchdown	The point, after a flight, at which an aircraft makes controlled contact by landing on runway's surface.
Terminal Maneuvering Area	Designated area of controlled airspace surrounding a major airport where there is high volume of traffic.
Vectoring	Navigation instructions issued by air traffic controller to pilots to fly aircraft specific headings at appropriate times so aircraft would follow a certain traffic pattern composed of legs or vectors

CHAPTER 1
INTRODUCTION

1.1 Background

Air transportation and aviation industries are facing several challenges in terms of projected increase in demand for travel and freight matched with limited resources in terms of airspace congestion and airport capacity. The International Air Transport Association (IATA) expects 7.2 billion passengers to travel in 2035, almost doubling the 3.8 billion air travelers in 2016, with the U.S. is the second fast-growing market, after China, with additional forecasted 484 million new passengers per year for a total of 1.1 billion passengers (IATA, 2016). With increased pressure on infrastructure in terms of terminals, runways, airspace around airports, and air traffic control operations, the industry is struggling to cope with this demand, yet it has to limit the impact that aircraft cause to environment in terms of Carbon emissions and noise levels.

With regard to aircraft emissions, a new release from the U. S. Environmental Protection Agency (EPA) has finalized a determination that greenhouse gas emissions from certain types of aircraft engines, primarily engines used on large commercial jets, contribute to the pollution that causes climate change and endangers Americans' health and the environment (EPA, 2016). Other countries are taking strict measures to limit emissions from aviation operations at airports by setting penalties for emissions levels above a specified limit. Under the European Union Emission and Trading System (EU ETS), all airlines operating in Europe, European and non-European alike, are required to monitor, report, and verify their emissions, to surrender allowances against those emissions that cover certain level from their flights per year (2017). Aircraft noise, on the other hand, is the biggest concern for airport officials at 29 airports of the 50 busiest U.S. airports (GAO, 2000). While airport support personnel who work in proximity to aircraft idling on the ground or taking off and landing may suffer hearing loss, residents of communities surrounding airports suffer sleep disorder and interference with speech both of which may lead to reduced productivity in learning and work. Furthermore, recent studies have linked noise to non-auditory health effects, such as hypertension, heart disease, and stroke (Basner et al., 2014). All the issues represent critical challenges to air transportation and aviation industry development and prosperity.

Continuous Descent Arrival (CDA), also known as Optimized Profile Descent (OPD), is an advanced flight technique for commercial aircraft to descend continuously from cruise altitude to Final Approach Fix (FAF) or touchdown without level-offs and with- or near-idle thrust setting. Descending using CDA procedure, an aircraft stay as higher as possible for longer time thereby expanding the vertical distance between aircraft's sources of noise and ground, and thus significantly reducing the noise levels for populated areas around airports. Also, by descending with- or near-idle engine setting, fuel burn is reduced resulting in reduction of harmful emissions to environment and fuel consumption to air carriers. A study conducted flight trials of CDA at Kentucky's Louisville International Airport using aircraft fleet of United Parcel Service (UPS), an express package delivery company, have quantified the benefits of CDA in terms of fuel savings by 400 lb to 500 lb per flight, and noise level by 3.9 A-weighted decibels (dBA) (Clarke, 2004). Another study conducted at San Francisco International Airport have estimated a reduction of CO_2 emissions between 700 lb and 10,000 lb per flight with CDA flights (Coppenbarger et al., 2009). Accordingly, these perceived environmental benefits, along with the resulting improved traffic flow, have made CDA to be often referred to in literature as the Green Approach (Stibor and Nyberg, 2009, Kuenz et al., 2007, Kuenz and Edinger, 2010).

Additionally, due to its operational nature of continuity, which differs from the widely-used step-down descent arrival (SDA), in which arrival aircraft descent in a step-like fashion, CDA saves flight time by around two minutes (Turgut et al., 2010a). FedEx Express, another express transport and delivery company with one of the largest civil aircraft fleets in the world, have implemented CDA between 2006 and 2009 at their World Hub; Memphis International Airport, which reduced flight time by 2.5 minutes for each flight, and this translated into cost savings of $105 million (Morrell, 2011). This saving in flight time is due to potential reduction in distance flown over the descent phase as well as elimination of level-off segments that normally increase flight time.

These operational, economical, and environmental benefits from CDA procedures made it a cornerstone in several aviation modernization programs at the national level (e.g., FAA's Next Generation Air Transportation System "NextGen"), continental (e.g., EU's Single European Sky Air Traffic Management Research "SEASAR"), and international (e.g., United Nations' International Civil Aviation Organization "ICAO" Continuous Descent Operations "CDO" initiative) levels. However, due to safety considerations, CDA procedures may require more separation between aircraft, which may affect the airport arrival rate and runway throughput. Thus, CDA implementation has been limited to low to moderate traffic levels. Insufficient several studies in the literature have used various approaches to present solutions to the problem of increasing the CDA implementation during periods of high traffic at airports, which typically occurs during daytime for airlines, and night time for logistics companies that uses aircraft for overnight delivery operations.

In this research, our focus is on CDA implementation during levels of higher traffic than currently existing. A special attention was dedicated to factors related to airports that has significant impact on CDA implementation, such airspace structure, airport arrival rate, and separation requirements for spacing aircraft arrivals for landing. Based on analyzing airspace structure around airport offers a systematic way of developing an analytical model that adequately captures the elements associated with descent and approach procedures, models are developed that aim at addressing the accommodation of more CDA operations during high traffic levels. The models introduced are divided into two main components; CDA Adoptability (CDA-A), and CDA Predictability (CDA-P). There are numerous studies in CDA literature focused on CDA implementation during high traffic levels, however, not sufficient attention has been given to developing a quantitative measure to enable air traffic controllers (ATC) making informed decisions with regard to accepting more CDA operations during high traffic levels. Based on this, the contribution of this work aims at developing models that address this gap in CDA research, that help ATC determines during periods of high traffic the threshold beyond which CDA would be unsafe to apply.

1.2 Adoptability of Continuous Descent Approach

To study and model CDA procedures during high levels of traffic at airports, we utilize Data Engineering and Analytics Approach, coupled with data-driven systems approach. Data Engineering and Analytics broadly refers to the interdisciplinary approach of using data science methods, such as methods and techniques for data mining, extraction, collection, transformation, and processing for knowledge discovery and to have insights on data to uncover hidden relationships and patterns that could be analyzed and communicated using advanced analytics for making informed decisions. In other words, Data Engineering and Analytics bridges data science; which include statistics, statistical machine learning and data mining, with decision science; which include operations research (OR), and experimental design, by learning from data (Hastie et al., 2013). Data-driven or data-adaptive system approach refers to the approach of design and analysis of systems based on data extracted from the components that help defines a system under study. Although relatively newly emerged, data-driven system approach has been widely applied to solve industrial and real-world problems in wide spectrum of fields including control engineering, aerospace, and manufacturing (Jian-Xin and Zhong-Sheng, 2009).

Utilizing data engineering and analytics approach, the first component of this research addresses the problem of increasing the level of CDA operations during levels of high traffic at airport by defining the concept of CDA Adoptability (CDA-A), which is defined as the level of CDA operations an airport can safely and efficiently accommodate and accept per hour. Although the concept often loosely used by ATC, this work is the first to present the term of CDA Adoptability. Mathematically, CDA-A is expressed by the CDA Adoptability Factor (CDA-AF), which is the ratio of average arrival hourly rate of CDA operations at an airport, to the total aircraft arrival hourly rate at that airport (i.e., Airport Arrival Rate "*AAR*"). The CDA-A model developed in this work help define and capture a threshold beyond which CDA becomes unsafe to adopt by analyzing airspace structure and airport parameters so two probabilities would be captured and presented, the first probability defines CDA threshold, while the second probability represents the upper bound of the system. In the CDA-A model, these parameters can be captured in a single measure, which we designate as Probability of Blocking, which is defined as the fraction of time an aircraft's request to embark on CDA is denied principally due to safety and because the stacking space within the TMA is busy and congested. Recalling that CDA operations do not need to be implemented to the *maximum* extent in order to yield beneficial fuel and emissions reductions (Shresta et al., 2009), but rather, a measure that strike the balance between safety, efficiency, more CDA operations, and thus more economic and environment gains. Essentially, the significance of this measure is to provide tactical guidance to ATC by helping answer a pressing question that ATC usually encounter during high traffic periods: *How many CDA operations the airport can safely and efficiently accommodate and up to what traffic intensity?*

1.3 Predictability of Continuous Descent Approach

We introduce and define Continuous Descent Approach Predictability (CDA-P) as the ability to accurately predict CDA operations based on specified features or attributes related to traffic and weather conditions. CDA-P represents the second component in this work to adopt more CDA operations during high periods of traffic at airports through prediction. To this end, a data-driven CDA model is developed using highly relevant data to flight arrivals for landing at airports. This data was obtained from off-line flight track logs which contains rich, spatio-temporal data on individual flights such as traffic level, aircraft type and speed, altitude, rate of descent, and exact location based on latitude and longitude coordinates that facilitate the capture of CDA flight for descent profile visualization as well as for building the CDA predictive model. In this research, a CDA *indirect* data-driven model was developed; that is, it aims at features or attributes extraction from *off-line* flight track logs that contains observations data of individual flights arrivals at an airport along with corresponding weather data from METeorological Aviation Report (*METAR*) decoded format for these flights. Figure 1.1 illustrates the attributes extracted to build the CDA indirect data-driven model.

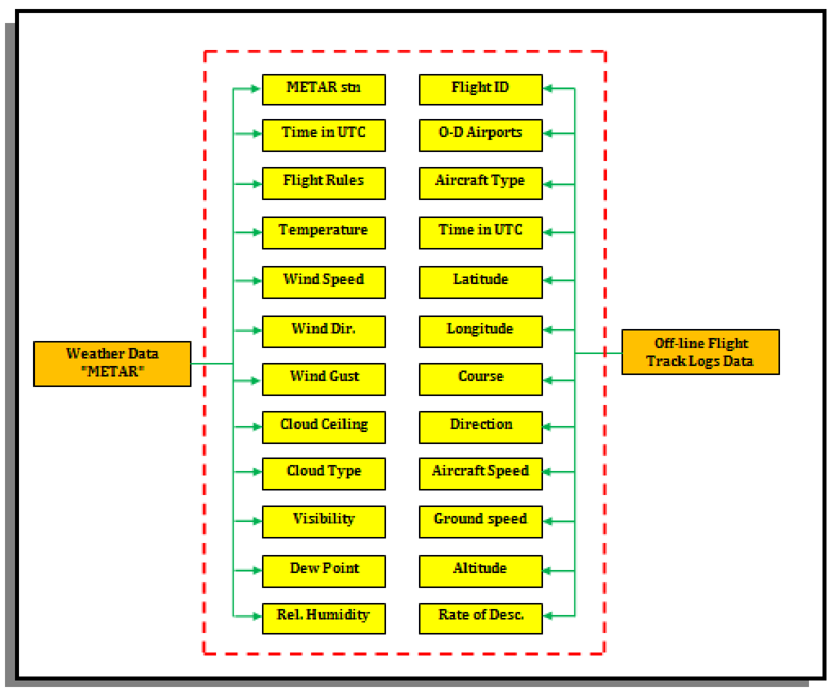

Figure 1.1 The indirect data-driven CDA model.

Finally, the two components in this work; CDA-A and CDA-P are connected together to help estimate and utilize the arrival rate of CDA operations. If the average arrival rate of CDA, λ_{CDA}, needs to be estimated, CDA-A model could be used at the strategic level. If λ_{CDA} needs to be predicted, verified, and validated, then CDA-P could be used, at the operational level, as shown in Figure 1.2.

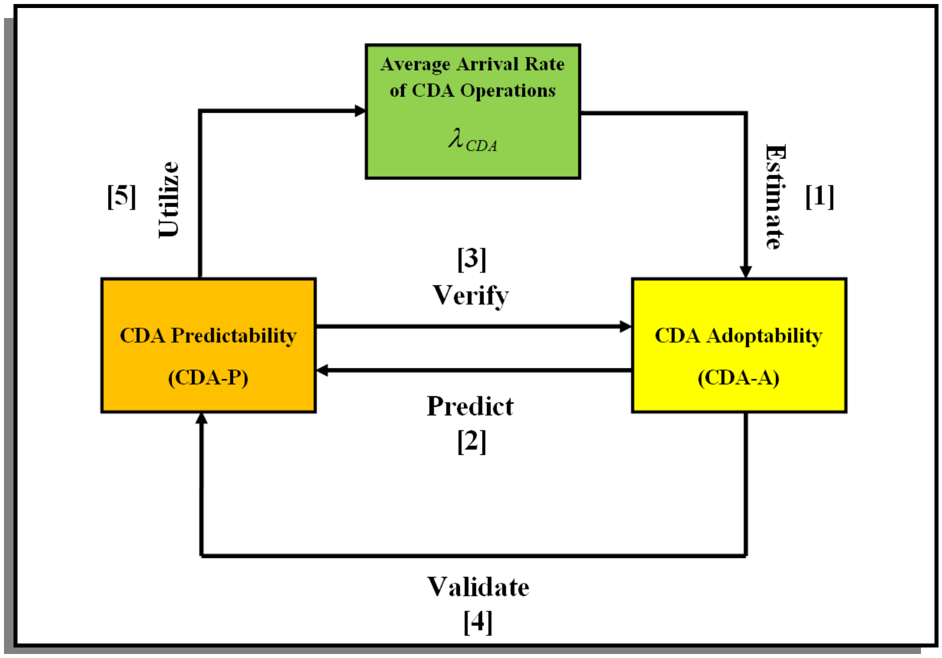

Figure 1.2 The relationship between CDA-A and CDA-P.

1.4 Research Objectives and Accomplishments

This research is organized into the research objectives described below. For each objective, the accomplishments described in the subsequent chapters is briefly summarized.

1. Investigate and study airspace structure around airports to identify factors that influence CDA operations implementation during high traffic levels. In details, describe and compare CDA and SDA in the light of these factors, and develop methods to estimate aircraft landing time under CDA and SDA operations.

Accomplishments: Extensive review to literature was conducted to study airspace structures for CDA implementation during periods of high traffic at airports. Special focus was dedicated to identify factors that play significant role in reducing CDA implementation at airports during high traffic levels. Based on extensive study to real world air traffic control (ATC) procedures, aircraft descent and approach operations were described in detail. The two most commonly used arrival and approach procedures; CDA and SDA, were described in details and further compared from several aspects. Two distinct methods used to estimate aircraft landing time; descent rules of thumb, and Base of Aircraft Data's (BADA) Aircraft Performance Model (APM). A computational algorithm was specifically developed to run descent rules of thumb in estimating landing time for aircraft, while BADA's Aircraft Performance Calculation (APC) tool was utilized to run BADA's APM computations.

2. Develop a model that help define and determine operational metrics for airports to assist air traffic controllers in better management and potential opportunity for increased CDA adoptability during high levels of traffic.

   Accomplishments: Models were developed that aim at addressing the accommodation of more CDA operations during higher traffic levels than currently acceptable. The models introduced are divided into two main components; CDA Adoptability (CDA-A), and CDA Predictability (CDA-P). By definition, CDA-A refers to the level of CDA operations an airport can safely and efficiently accommodate and accept per hour. Mathematically, CDA-A is expressed by the CDA Adoptability Factor (CDA-AF), which is the ratio of average arrival hourly rate of CDA operations at an airport to total aircraft arrival hourly rate at that airport (i.e., Airport Arrival Rate "*AAR*"). The CDA-A model was introduced to define and capture a threshold beyond which CDA becomes unsafe to adopt. Based on our analysis, two probabilities were captured and presented, the first probability defines CDA threshold, while the second probability represents the upper bound of the system. Parameters, such capacity of stacking space, and separation between aircraft were captured in a single measure, which we designate as Probability of Blocking, and define as the fraction of time an aircraft's request to embark on CDA is denied principally due to safety and because the stacking space within the airport's terminal maneuvering area is busy and congested.

3. Develop a framework that can be utilized to build predictive models capable of predicting CDA instances, with high accuracy, during high levels of traffic at airports.

   Accomplishments: To predict CDA instances during high levels of traffic at airports, CDA-P model is introduced. CDA-P utilizes a framework developed based data-driven system approach to build an indirect data-driven CDA model, which composed of traffic and weather components, to build predictive models that predict CDA instances at airports during high level of traffic. The framework consists of two main modules Descent Profile Analytics, and CDA Predictive Analytics, and starts with acquiring off-line flight tracks logs that contains spatio-temporal data generated from ADS-B (Automatic Dependant Surveillance-Broadcast) systems for each flight arrived at a given airport. Exploratory data analysis and Hierarchal Clustering Analysis (HCA) are conducted to flight data to visualize and label the descent profile of each flight (i.e., CDA or Non-CDA). As part of the CDA Predictive Analytics Module, statistical classifiers used to build CDA predictive models. To build a CDA predictive model, dataset was created and partitioned into three, independent subsets; 70% for training, 15% for validation, and 15% for testing. This partitioning was done randomly to ensure each subset is representative to the whole collection of observations in the dataset. CDA predictive model was built—and trained— using the training dataset.

4. Utilizing the developed framework and suitable actual flight data, build predictive models to predict CDA instances during high level of traffic at a selected airport. Train, test, and validate CDA predictive models using two distinct predictive algorithms, then evaluate and compare the performance of each model.

   Accomplishments: Data extracted from off-line flight tracks logs to create datasets and utilizing the developed framework, two distinct statistical classifiers used to build CDA predictive models. The first classifier is an ensemble classification model that combines multiple decision trees into a single model with boosting method to improve the prediction accuracy of CDA instances, which decision trees with Adaptive Boosting (AdaBoost), while the second classifier is Support Vector Machines (SVM) that extends the support vector classifier to non-linear boundary between binary classes by enlarging the feature space. Evaluating the performance of the two predictive methods, the predictive model built with AdaBoost was found to outperform its counterpart with SVM in terms of accuracy rate and sensitivity.

1.5 Organization of the Dissertation

This dissertation is organized as follows. Chapter 1, provides a background of the problem and enumerated the objectives of the thesis. Chapter 2 conducts a detailed literature review to provide the motivation of the work highlighting the contributions of the existing solutions, current approaches, and justifying the contribution needed in the CDA research arena. Chapter 3 presents preliminaries considered in formulating the CDA Adoptability model as well as describe airspace structures around airports along with descent and approach operations. This chapter also describe and compare, in details, the two types of descent profiles; CDA and SDA, and presents estimation for the time aircraft may takes to land using these two descent profiles through the use of two different methods; descent rules of thumb, and Base of Aircraft Data's (BADA) Aircraft Performance Model (APM). Chapter 4 details the underlying assumption, parameters considered, and development of the CDA Adoptability model. It also defines the Probability of Blocking, P_k; the metric that estimates the threshold beyond which CDA is unsafe to be adopted during periods of high traffic. Application of CDA Adoptability model is presented through a numerical example using simulated data, along with validation of the CDA Adoptability model is also presented in Chapter 4 by applying the model on actual flight data. Chapter 5 presents CDA predictability model, in which a data-driven framework is developed that utilize indirect data-driven CDA model to build CDA predictive models able to predict CDA instances during high traffic levels at airports, and could ATC see fit to implement. Finally, Chapter 6 presents the conclusions of this dissertation and recommends directions for future research.

CHAPTER 2

LITERATURE REVIEW

The main goal of this chapter is to describe and classify approaches and methods used in the literature to address the problem of Continuous Descent Approach (CDA) implementation. By examining major works in CDA literature, Sections 2.1, 2.2, and 2.3 of this chapter present definitions of CDA, benefits, and its challenges, respectively. Section 2.4 reviews the approaches used to identify factors that affect CDA implementation, with studies used simulation approaches are reviewed in subsection 2.4.1, while subsections 2.4.2 and 2.4.3 covers studies appeared in literature that model CDA procedures analytically and mathematically, as well as studies used in flight trials to demonstrate CDA procedures, respectively.

2.1 What is Continuous Descent Approach (CDA)?

At its basic description, Continuous Descent Approach (CDA), also referred to as Optimized Profile Descent (OPD), could be defined as the advanced flight operating technique for landing through which an approaching aircraft descent from cruise altitude to touchdown in a smooth, continuous fashion, with- or near-idle engine setting. While such definition may have considered relatively simple, other definitions developed and adopted by civil aviation and air traffic management (ATM) bodies at the international and national level provides more comprehensive, highly detailed description to CDA. For instance, the United Nations' (UN) International Civil Aviation Organization (ICAO) define CDA under a broad, generic term of Continuous Descent Operations (CDO) as:

> *An aircraft operating technique aided by appropriate airspace and procedure design and appropriate ATC clearances enabling the execution of a flight profile optimized to the operating capability of the aircraft, with low engine thrust settings and, where possible, a low drag configuration, thereby reducing fuel burn and emissions during descent. The optimum vertical profile takes the form of a continuously descending path, with a minimum of level flight segments only as needed to decelerate and configure the aircraft or to establish on a landing guidance system* ((ICAO), 2010).

In addition, ICAO emphasizes that the term CDO has been adopted to embrace the various techniques being applied to maximize descent operational efficiency to cover operations known as Continuous Descent Arrival, Continuous Descent Approach, Optimized Profile Descent, and Tailored Arrivals.

Similarly, the European Organization for the Safety of Air Navigation, commonly known as EUROCONTROL, which is the regulating body on safe and efficient ATM operations across Europe, has adopted the following definition for CDA:

> *An aircraft operating technique in which an arriving aircraft descends from an optimal position with minimum thrust and avoids level flight to the extent permitted by the safe operation of the aircraft and compliance with published procedures and ATC instructions* (EUROCONTROL, 2011).

In the United States, the FAA classify CDA according to the operational nature of the procedure used in the NAS into two types (Robinson and Kamgarpour, 2010b):

1. **Optimized Profile Descent (OPD):** represents published arrival procedures designed with altitude restrictions to accommodate varieties of aircraft types, and thus they are not aircraft-specific. Using this procedure, aircraft will be able to perform CDA until interrupted by ATC. OPD has been operationally used at several major airports, such as Los Angeles (LAX), Atlanta (ATL), Louisville, Kentucky (SDF), Las Vegas (LAS), and Phoenix, Arizona (PHX).

2. **Tailored Arrival (TA):** represents trajectories that have been dynamically designed and tailored to specific aircraft type, thus they are aircraft-specific. Normally, TAs are generated by ATC to account for traffic level, weather conditions, and sequencing criteria. TAs have been operationally used at airports major such as San Francisco (SFO), LAX, and Miami (MIA).

2.2 Benefits of CDA

The importance of CDA lies in the potential benefits and contributions in the economic, environmental, operational, and traffic aspects when implementing such procedures. Benefits of CDA procedures include reduction in environmentally damaging emissions from aircraft engines; as such, reducing of aircraft's fuel consumption; noise level at airports; and overall flight time and delay, as well as translates as more efficient utilization to airspace; and thus, CDA provides benefits to all air traffic stakeholders, such as air carriers, air navigation services providers (ANSPs), airport operators, and civil aviation regulators (Wilson and Hafner, 2005). In addition, CDA contributions in terms of gain of capacity, reduction of environmental impact, improved flight efficiency, and high predictability (Kuenz and Edinger, 2010). This contributions could expectedly yield three benefits of implementing CDA operations; advance trajectories predictability that improve planning, safety from accurate aircraft positioning, and reduce environmental impact and improve cost efficiency by optimizing routing and fuel burn (Kuenz and Edinger, 2010).

Flight demonstrations conducted at Louisville International Airport (SDF), Kentucky, with Boeing 767-300 aircraft have shown that CDA procedure can reduce noise from 9.5 to 6.5 dBA (*Decibels noise unit that weighted with an "A" filter to account for human hearing characteristics*), knowing that 3 dBA is noticeable to the human ear; and fuel consumption from 900 to 500 pounds per flight (Clarke, 2004). A simulation-based study used the high-fidelity simulation software Total Airspace and Airport Modeler (TAAM), and flight data of Atlanta's Hartsfield-Jackson International Airport (ATL) to assess the effects on airlines if CDA procedures were to be implemented found that CDA implementation yield savings in flight time, airspace delay and fuel consumption of more than $29 million in ATL airport only (Wilson and Hafner, 2005). Another study quantified the benefits of noise and emissions reductions in Los Angeles International Airport (LAX) using the FAA's Aviation Environmental Design Tool (AEDT) and EUROCONTROL's Aircraft Noise and Performance (ANP) database found that during CDA procedures total flight time decreased; and as a result to reduced thrust levels, fuel burn and Nitrogen oxides (NO_x), Carbon dioxide (CO_2), Sulfur oxides (SO_x), and water vapor (H_2O) were decreased accordingly (Dinges, 2007). Finally, a simulation-based study used real flight data from B757 aircraft in Istanbul's Terminal Maneuvering Area (TMA) found that CDA could reduce flight time by two minutes and fuel consumption by more than 40 kg, with significant reductions in emissions of CO_2 and H_2O at the entry point to the TMA considered in their study (Turgut et al., 2010b).

2.3 Challenges of CDA

With particular emphasis on congested terminal areas, major challenges when implementing CDA procedures lies in the variability inherited in both, flown descent trajectories, and aircraft types (Jackson, 2009). However, the major challenge that delays the deployment of CDA procedures is not related to current technology; rather, it is in the lack of integration between today's air and ground-based systems. This lack of a process that facilitates a smooth transition to the efficient trajectory-based operations delays the upgrades of air and ground-based systems (Kuenz and Edinger, 2010).

Until recently, the current utilization of CDA procedures has been limited to low traffic levels because it would be very hard for the pilot to react on ATC instructions once the idle descent is commenced. Accordingly, the challenges of CDA operations implementation during daytime may include inadequacy of current ATC procedures and technology, the lack of standard operating procedures for CDA, and the incapability of many aircraft types to fully utilized CDA operation (Lenz and Korn, 2009). Thus, the implementation of CDA in the present time is not efficient as it should be in moderate to high traffic because it mandates greater spacing between aircraft arrivals than the standard landing procedures. Therefore, in order to implement CDA, ATC must precisely recognize the time at which aircraft are at the right distance from the airport to clear the initiation of descent procedures (LaMarr et al., 2011). Finally, the inaccurate prediction of an aircraft's TOD point location is also an operational challenge for CDA implementation. With the investigation of factors like aircraft type or series, winglets, and engine thrust would help understand the nature and magnitude of impact of such and any related factors on the accuracy and performance of trajectory automation systems (Johnson, 2011).

2.4 Current Approaches in CDA Research

CDA has attracted researchers' attention in the last decade or so. As a result, numerous works has been dedicated to study CDA with objectives covers wide spectrum of areas including benefits quantification, merging and spacing assurance; both horizontally and vertically, conflict detection and resolution, technology evaluation, runway capacity and throughput analysis, navigation and trajectory optimization, human factors in CDA, and legal and policy development. To carry out these scientific works, researchers used approaches such as simulation, mathematical, and flight trials to demonstrate the value of CDA as a feasible noise abatement procedure with *green* and economic benefits.

2.4.1 Simulation Approach

Due to the complex nature of air traffic management (ATM) system around airports, and this complexity will gradually increase with the gradual deployment of new and advanced technology into the national airspace system (NAS) through the air transportation upgrade programs (e.g., FAA's Next Generation Air Transportation System "NextGen") (Lyons, 2012), simulation approach has been widely used in CDA research.

Wilson and Hafner used fast-time simulation conducted on Total Airspace and Airport Modeler (TAAM) simulation tool to assess the benefits of airlines using CDA at Atlanta's Hartsfield-Jackson Int'l Airport (Wilson and Hafner, 2005). With conjunction with average daily arrivals for a single operating configuration at Los Angeles International Airport (LAX), Dinges modeled CDA operations to evaluate the benefits of potential future levels of CDA implementation as a function of traffic density using the FAA's Aviation Environmental Design Tool (AEDT) (Dinges, 2007). For trade-off analysis between CDA trajectories and airport capacity in high traffic, (Kuenz et al., 2007) used research aircraft for flight trials and simulation experiments with the A330 full slight simulator. To investigate precision airborne spacing between aircraft arrivals flying CDA, (Barmore et al., 2008) used low-fidelity Traffic Manager (TMX) simulator in their study. Finally, (Novak et al., 2014) developed a simulation tool to assess the environmental and operational benefits of implementing CDA at Zagreb and Split airports of Croatia.

As stated earlier, numerous studies that can be found in CDA literature has used the simulation approach, whether solely or with conjunction with experimental flight trials. Most of these studies provide tangible and valid results, whether used some highly-sophisticated, government and/or company proprietary, or user-built simulation tools, however, insufficient attention was given to provide metrics for adopting CDA.

2.4.2 Analytical and Mathematical Modeling Approaches

Analytical and mathematical approach to model CDA procedures during daytime operation has been present in CDA literature, however, not as much as simulation-based approach studies. Perhaps this attributes to the computation complexity to solve the mathematical model of CDA. For instance, (Khardi, 2010) developed an optimization model with various components, such as ordinary differential equations for flight dynamics of aircraft in space, constraints for flight configurations, flight safety, and comfort requirements, were formulated as an optimal control problem. The main objective of the author was to minimize noise levels and fuel consumption during approaches and departures, and to reach this objective, he discretized the control and state, and transform the optimal control problem into a nonlinear programming problem. He found that CDA to be the optimal approach procedure for minimizing noise and fuel consumption. With the same objectives and same approach, (Khardi, 2012) developed a trajectory generation algorithm based on Hamilton-Jacobi-Bellman method to determine the optimal flight approach. By considering one noise source for one aircraft type and with no consideration to wind effect, the author found that a CDA with one-segment could be the optimal trajectory for approach.

Analytically, and by using Base of Aircraft Data's (BADA) Total Energy Model (TEM), (R. Arnaldo Valdés, 2009) developed a mathematical model for CDA procedures at Spain's Madrid Barajas Int'l Airport. (Robinson and Kamgarpour, 2010a) analytically estimated the potential benefits of CDA at 25 major U. S. airports. To investigate the optimized descent trajectories for different types of aircraft for appropriate arrival sequencing to reduce emissions and minimize fuel consumption, (Andreeva-Mori et al., 2011) used a point-mass aircraft model to analyze CDA procedure. Whereas (Cao et al., 2011b, Cao et al., 2011a) presented a rescheduling algorithm for aircraft flying CDA that minimize total delay and resolve conflict by formulating the problem as a mixed integer linear program and solved it using CPLEX software, and by implementing their algorithm on a full day of flight data of Newark Liberty Int'l Airport found that conflict-free CDA could save 80 tones and 638 minutes of flight time. Finally, with aim to determine an optimal policies for sequencing and separation of OPD flights, (Chen and Solak, 2015) developed a stochastic dynamic programming framework and analytically solve for those optimal policies' decisions, and by simulating their findings on Atlanta's

Hartsfield-Jackson International Airport, they found that annual savings of $29 million could be gained by top ten major U. S. airports.

Similarly to simulation approach studies, these mathematical approach studies used sophisticated analytical methods to provide tangible and valid results, however, no operational threshold to adopt CDA at airports were presented.

2.4.3 Flight Tests and Demonstration Approaches

Several studies in CDA literature used flight trials and demonstration for aircraft flying CDA procedures. Also, the flight tests and demonstration in CDA literature has many focuses and findings. For instance, a major study that aims to design and test-flight CDA as a noise reduction flight procedures at Louisville Int'l Airport was conducted by (Clarke et al., 2004). The authors found that CDA significantly reduced noise level and fuel for United Parcel Services' (UPS) Boeing B737-800 aircraft. For the same objective, similar studies were also conducted at United Kingdom's Nottingham East Midlands Airport (Reynolds et al., 2007), Croatia's Zagreb International Airport (Novak et al., 2009), Poland's Warsaw International Airport (Gągorowski, 2012), and Los Angeles International Airport (Clarke et al., 2013).

By using a data-link between a ground station and aircraft to enable CDA, (Coppenbarger et al., 2009) evaluated the concept of oceanic Tailored Arrivals (TAs) as an aircraft-specific CDA procedures, for Boeing B777 aircraft at San Francisco International Airport, and found that from the demonstration that TAs could provide efficient CDA operations under real-world conditions. Finally, by testing special Standard Terminal Arrival Routes (STARs) that enable CDA from cruise altitude to runway threshold for Scandinavian Airline's B737 aircraft, (Stibor and Nyberg, 2009) implemented CDA at Sweden's Stockholm Arlanda Airport. The authors found that Area Navigation (RNAV) STAR enabled increase in the monthly rate of CDA flights flown, and raise the question of *at what traffic density the number of CDA-flights can be achieved with current and future infrastructure*?

It is important to note that the previously mentioned studies have utilized sophisticated approaches by testing and demonstrating CDA flights at airports, and presented viable results, such as the proof of CDA feasibility as a noise abatement flight procedure for populated vicinities around airports and the development of new CDA-compatible STARs. Nevertheless, they have not sufficiently present threshold for CDA implementation considering airport specifics and traffic condition. This is what motivates this research, and as can be seen from the aforementioned review, insufficient attention was given to the development of thresholds to maximizing the adoption of CDA procedures at airports during high traffic periods. More specifically, this work develops models that defines quantitative measure determines threshold beyond which CDA adoption would be unsafe.

CHAPTER 3

PRELIMINARIES AND PROCESS DESCRIPTION

This chapter presents a detailed description of the two most commonly used landing approaches of aircraft; Continuous Descent Approach (CDA), and Step-down Descent Approach (SDA). The main goal of this chapter is to provide the necessary preliminaries that determine which of these landing approaches is more appropriate as they apply to the specific airport particulars and flying conditions. We begin by describing the airspace around airports and its fixes; fully describe each of the two approaches; introducing the concept and factors that influence CDA Adoptability; then using two different methods estimate the time aircraft takes to land under these two approaches.

3.1 Preliminary

Demand on air transportation for passengers and air cargo continues to grow in volume. By the year 2030, scheduled passenger traffic around the world is expected to more than double, from 2.7 billion in 2011 to 6 billion annually, with similar upward growth trend in air cargo (Organization and internationale, 2013). This increasing demand adds more workloads on the current airports infrastructure and air traffic management (ATM) system. Satisfying these additional workloads would not be possible with over-matured ATM technology and limited airports capabilities. As it relies on outdated technology, the current ATM procedures yet would not be able to handle the present and future increase in flight operations in terminal airspace.

Continuous Descent Approach (CDA), also referred to as Optimized Profile Descent (OPD), is the advanced flight technique for landing through which an approaching aircraft descent from cruise altitude to touchdown in a smooth, continuous fashion, with- or near-idle engine setting. Unlike the conventional Step-down Descent Approach (SDA), CDA minimizes thrust utilization to avoids level-offs during descent. When implemented properly, CDA proved to remarkably reduce fuel consumption, noise levels, and harmful emissions, and provide efficient utilization to terminal maneuvering airspace (TMA) through more streamlined flight trajectories. Such benefits are aimed by all stakeholders alike including civil aviation regulators, airport operators, and air carriers. As such, CDA considered a cornerstone in national, continental, and global efforts aimed to modernize and improve aviation operations and air transport industry, such as United States' Next Generation Air Transportation System (NextGen)(Joint Planning and Devlopment Office, 2011), Europe's Single European Sky ATM Research (SESAR) programs (Commission, 2009), and ICAO's Continuous Descent Operations (CDO) initiative ((ICAO), 2010).

Many airports in the U. S. and around the world are attempting to adopt—and increase the level of adoption—of CDA, however, due to issues related to safety considerations in horizontal separation during the approach phase of fights and predictability in descent profile that may negatively be reflected on airport arrival rate and runway capacity, CDA adoption at airports have been limited to low to moderate traffic levels, and thus, the level of gain of CDA's environmental, economic, and operational benefits would be reduced. Several research works have attempted to address the problem of increasing CDA Adoptability (a concept that will be presented later in this chapter), especially during periods of high demand at airports operation, utilizing a variety and combination of traditional methods including analytical, simulation, and flight trials. Although such methods have proved feasible solutions, they were either limited in scope, utilized proprietary simulation tools, or required expensive experimentation setup.

With aim to support CDA adoption during airports' normal operating hours, this work attempt to help decision makers make informed decisions on increasing the level of CDA adoption. The main hypothesis of this research is that there are factors related to airports' operational and meteorological characteristics that have influence on the level of CD adoptability, which could be investigated to develop a threshold for CDA operations.

3.2 Structure of Airspace and Arrival Procedure around Airports

3.2.1 Terminal Maneuvering Area

Terminal Maneuvering Area, shortly known as TMA, refers to the designated area of airspace controlled by air traffic control (ATC) services around major airports that has high volume of traffic. Normally, TMA airspace is designed in a circular configuration centered around the geographical coordinates of the airport. Arriving aircraft enters the TMA airspace via entry fixes or arrival fixes, which defines the TMA boundary and considered as entry points to the TMA. When crossing the TMA boundary over one of these entry fixes, the responsibility for separating aircraft will be handed-off usually from controller at the air traffic control center responsible for separating en route aircraft (i.e., Air Route Traffic Control Center "ARTCC") to controller at the air traffic control center responsible for separating aircraft approaching airport (i.e., Terminal Radar Approach Control "TRACON"). A typical structure for a TMA is illustrated in Figure 3.1 below.

The configuration of entry fixes shown in Figure 3.1 represents multiple-post arrangement used for airspace unconstrained by major physical obstacles, such as mountainous terrains. The designation and location of active entry fixes; that is, the ones that can be used by arriving aircraft, depends on the traffic pattern used by Air Traffic Controllers (ATC) and air traffic level at airport .

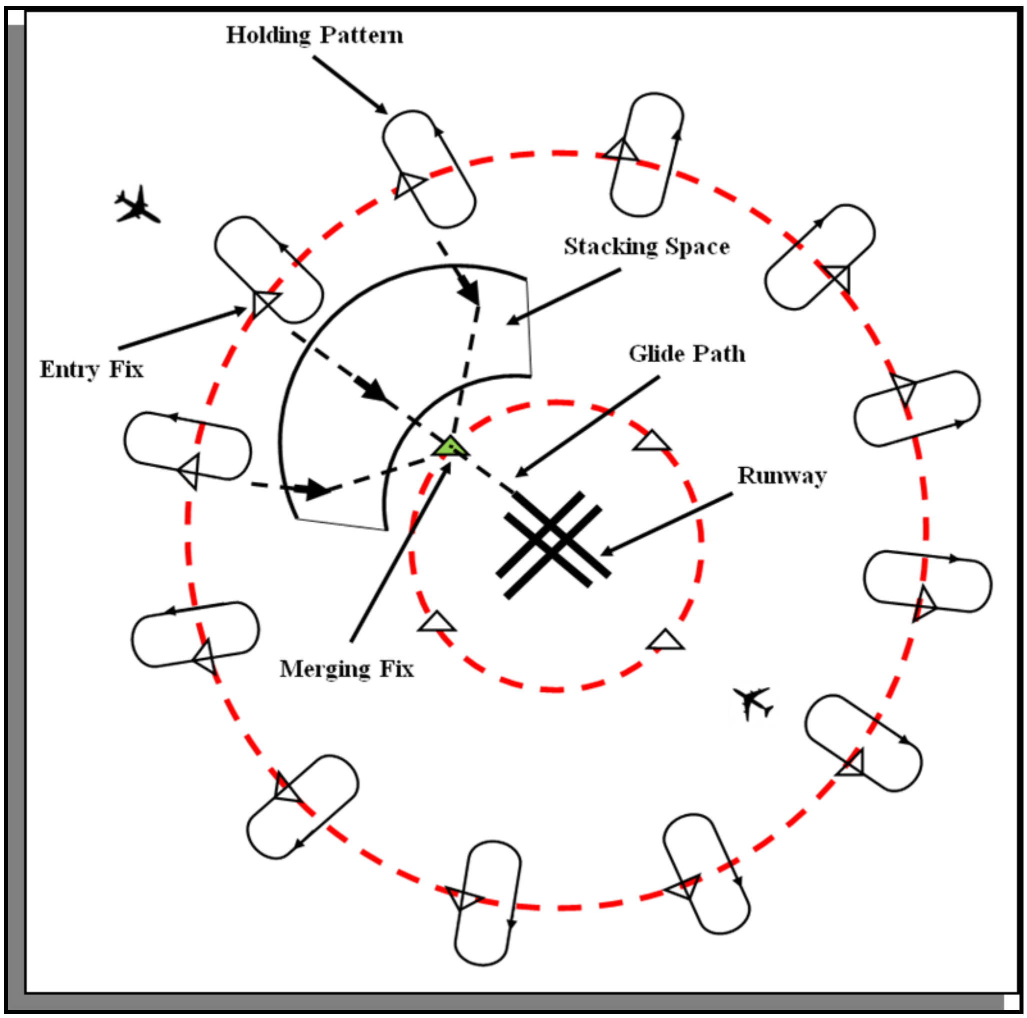

Figure 3.1 Typical structure of a TMA.

As arriving aircraft nears an entry fix, ATC may clear the pilot for approach or, depending on traffic congestion and separation and sequencing method used, may place the aircraft on a holding pattern. The holding pattern keeps the aircraft within a specified airspace while awaiting further clearance from the ATC. By doing so, ATC will be able to regulate the air traffic flow and utilize efficient sequencing method for safe separation, especially during periods of high volume of traffic. This safe separation is essential for traffic sequencing and efficient ATM at this point as ATC uses the volume of terminal airspace available for stacking arriving aircraft waiting to land.

Once aircraft cleared by ATC to approach or to leave holding pattern, if placed on it, the aircraft approach the merging fix. However, as the aircraft approaching the merging fix, it flies in the stacking space; the space that ATC use from the available terminal airspace to stack arriving aircraft. In the stacking space, ATC manage air traffic and enhance airspace capacity by stacking arriving aircraft using techniques such minimal speed adjustments and path-stretching. This efficient management of air traffic flow enable ATC to bring together aircraft that have crossed entry fixes from different directions to be stacked and merged at the merging fix. The merging fix provides transition for arriving aircraft from the stacking space to approach as it connects traffic from different directions into one stream to follow a standard published arrival procedure. This way, arrivals from several directions can be accommodated and traffic flow is managed efficiently within a congested airspace. In order to safely and successfully merge arriving aircraft, ATC synchronize aircraft joining time on the air route leading to the merging fix considering sufficient spacing for other aircraft to fit into the air traffic stream and while maintaining, at least, the minimum required separation between aircraft.

3.2.2 Point Merge

Point Merge (PM), is a systematized method for merging and sequencing aircraft arrivals flows that has been designed and developed by EUROCONTROL Experimental Center in 2006 to enable significant use of lateral guidance by the Flight Management System (FMS) and facilitate continuous descent, even under high traffic load. PM has a specific route structure, referred to as Point Merge System (PMS), comprised of a point (the merge point) and pre-defined legs (sequencing legs) with equal distance from this point but vertically separated. Operationally, the PMS provides smooth transition or initial approach procedure through two main steps: 1) Create spacing by a "direct to" instruction from the ATC to each aircraft to direct from the sequencing leg to the merge point at the optimal sequencing time, and 2) Maintain the spacing by speed adjustment after leaving the sequencing leg (Favennec et al., 2009). Figure 3.2 below illustrates a PMS with two entry-points.

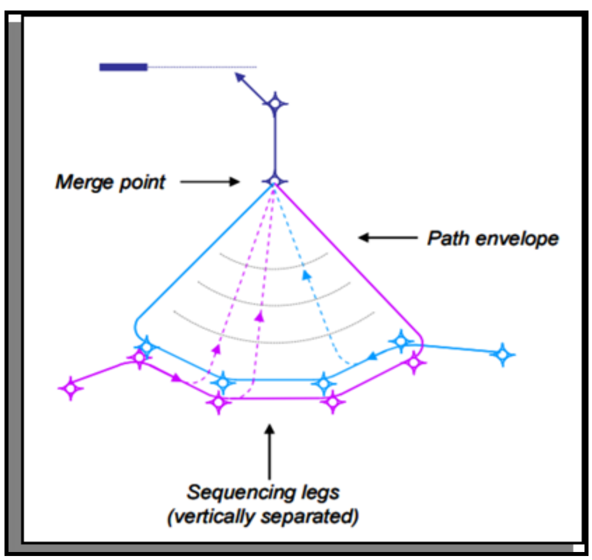

Figure 3.2 Point Merge System (PMS) with two-entry points.
Source: Favennec, B., Hoffman, E., Trzmiel, A., Vergne, F., & Zeghal, K. (2009) "*The Point Merge Arrival Flow Integration Technique: Towards More Complex Environments and Advanced Continuous Descent*" Paper presented at the 9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO).

3.3 Description of Aircraft Descent and Approach Process at Airports

3.3.1 Descent and Approach Operations

Typically, the descent could be initiated to attain an optimal profile from cruise all the way down to landing to minimize fuel burn, emissions, and noise exposure. However, due ATC restrictions and aircraft performance limitations, this optimal descent profile may not all the time attained. For aircraft operating at typical cruise altitudes, descent will nominally initiate at 100 to 130 nautical miles (nmi) from the destination airport. This distance primarily varies as a result of ATC restrictions, aircraft's equipment and performance capabilities, and weather conditions. ATC may issue crossing restrictions during the descent, as part of a STAR (Standard Terminal Arrival Route), or as a requirement for traffic sequencing. These crossing restrictions are generally issued to cockpit crew in terms of altitude over a fix, or may include a speed restriction as well (Belobaba et al., 2015).

A stabilized descent requires minimum control input to maintain the planned descent path; that is, excessive corrections or control inputs indicates that the descent was improperly planned. Thus, planning the descent from cruise altitude is important because descending early results in more flight at low altitude with increased fuel consumption, and starting down late results in problems controlling both airspeed and descent rates later on the approach phase.

Prior to flight, pilots need to compute the fuel, time, and distance required to descend from the cruising altitude to the approach gate—an imaginary point used by ATC to vector aircraft arrivals to the final approach course—with objective to determine the most economical point for descent; referred to as the Top of Descent (TOD) point.

The computations for TOD point could be done manually prior to flight or automatically during flight using the Flight Management System (FMS). While in flight prior to the descent, pilots plan the descent from cruise by verifying landing weather to include winds at their consideration since inclimate weather at the landing airport can cause slower descents. Furthermore, pilots need to know the cruise altitude, approach gate altitude or initial approach fix (IAF) altitude, descent groundspeed, and descent rate.

Based on aircraft performance, approach constraints, aircraft weight, and weather data; such as winds, temperature, and icing conditions; the vertical component of the flight plan, referred to as the Vertical Navigation (VNAV) is computed. Usually, the VNAV approach is computed from the TOD point down to the waypoint at which descent ends, which is generally the runway or Missed Approach Point (MAP). There are only two types of VNAV paths that the FMS use; performance path or geometric path. The performance VNAV path is computed using idle or near-idle thrust from the TOD point to the first constrained waypoint, which represents a typical Continuous Descent Approach (CDA). While the geometric VNAV path is computed from point-to-point between two constrained waypoints or when a vertical angle is assigned, which may represent a typical Step-down Descent Approach (SDA) as it is shallower than the performance VNAV path and is typically use a non-idle thrust. Detailed description to CDA and SDA is presented in the following sections.

3.3.2 Step-down Descent Approach (SDA)

In air navigation, if the aircraft flies under Instrument Flight Rules (IFR), which represents a set of rules governing the navigation of aircraft using instruments, then the instrument approach procedures (IAP) must be conducted. IAP consists of three approach segments along the aircraft flight path; namely, initial, intermediate, and final approach, and a point for missed approach. Typically, initial approach segment starts at en route (i.e., cruise) altitude from an initial approach fix (IAF), and ends when the aircraft joins the intermediate approach segment, where the later ends at the final approach fix (FAF). Step-down Descent Approach (SDA) refers to the conventional arrival procedure that pilots and ATC has been accustomed to for many years. In SDA, aircraft begins initial descent at the TOD point and continue descending gradually in a series of steps along the descent path. This step-down descent occurs as a result of aircraft leveling off from current altitude to new altitude, due to ATC instructions and/or airspace constraints.

During the SDA, aircraft gradually level-off by transitioning from initial to intermediate to final approach segments through predefined fixes that indicates the start and end of each approach segment. To fly from the fix that marks the end of the previous approach segment to the fix that marks the subsequent one, aircraft must increases speed by employing thrust to maintain level (Nolan, 1999). Depending on the airspace structure, traffic intensity and congestion, and ATC directions, the number of aircraft level-offs varies and may increase.

It can be seen that the SDA requires more fuel burn to maintain level while aircraft transitioning between approach segments; and more fuel burn means more fuel consumption, more green house gas emissions as well as noise generation due to engine's power utilization. SDA also requires more communication between pilot and ATC to inform and authorize air movement, which means more workload on both aircrew and ATC during a critical phase of flight that requires situational awareness and additional concentration. Figure 3.3 illustrates the SDA profile and the approach segments of an IAP.

As the aircraft step-down and transition from initial through intermediate to final approach segments, the pilot needs to reduce aircraft speed and maintain appropriate rate of descent to establish the aircraft in a stabilized descent. Once the aircraft have reached the fix or waypoint that marks the end of the previous approach segment and marks the subsequent one at new altitude assigned by ATC, the pilot needs to utilize engine thrust in order to maintain level and prepare for further instructions from the ATC with respect to approach. Although air traffic may be expedite during periods of high demand at airports when using SDA through ATC vectoring, however, the utilization of engine power increase fuel burn, which in turn, increase emissions and noise levels at lower altitudes (Nolan, 1999).

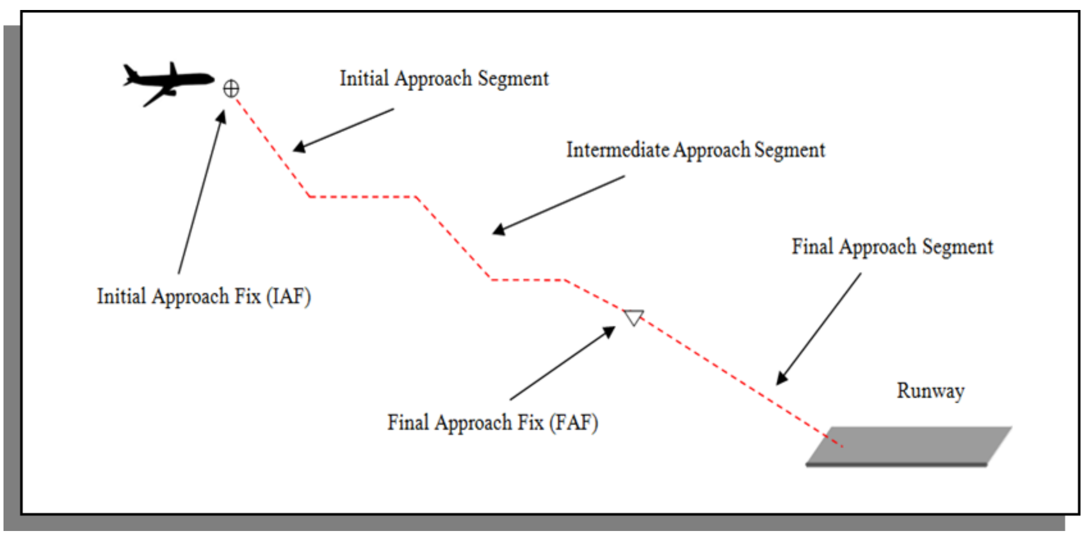

Figure 3.3 The vertical profile of SDA based on the IAP and approach segments.

3.3.3 Continuous Descent Approach (CDA)

As previously mentioned, CDA is the advanced flight technique for landing through which an approaching aircraft descent from cruise altitude to touchdown in a smooth, continuous fashion, with- or near-idle engine setting. As the name implies, CDA characterized by the continuation feature for aircraft's descent, which requires no interruption in order to conduct the procedure properly and gain environmental and operational benefits. That is, unlike the SDA, aircraft conducting CDA will be smoothly and continuously descending along the descent flight path over the entire three IAP approach segments. Also, the engine thrust setting to idle reduces thrust employment, which in turn reduces fuel burn, emissions, noise exposure, and provides low drag configuration that improves aircraft aerodynamic performance and stability during descent (Clarke, 2004).

Unlike the SDA, CDA minimizes thrust utilization to avoids level-offs during descent. When implemented properly, CDA proved to remarkably reduce fuel consumption, noise levels, and harmful emissions, and provide efficient utilization to terminal maneuvering airspace through more streamlined flight trajectories by reducing zigzagging approaches, also known as doglegging. As shown in Figure 3.4, ATC often instructs pilots through vectoring to approach runway in a zigzag pattern in order to manage high traffic while accepting more aircraft for landing. Since CDA benefits are aimed by all stakeholders alike including civil aviation regulators, airport operators, and air carriers, it is considered as a cornerstone in national, continental, and global efforts aimed to modernize and improve aviation operations and air transport industry, such as United States' Next Generation Air Transportation System (NextGen), Europe's Single

European Sky Air Traffic Management Research (SESAR) programs and ICAO's Continuous Descent Operations (CDO) initiative. Figure 3.5 illustrates the vertical profile of CDA compared with SDA.

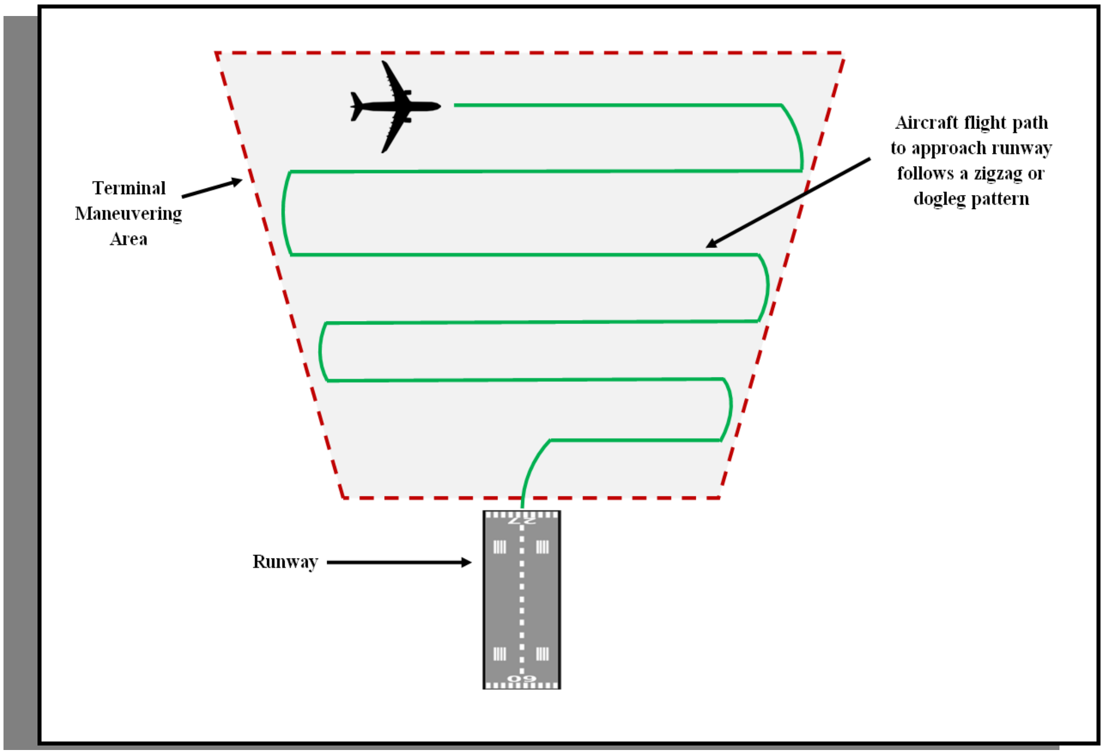

Figure 3.4 The zigzagging (also known as doglegging) approach to runway.

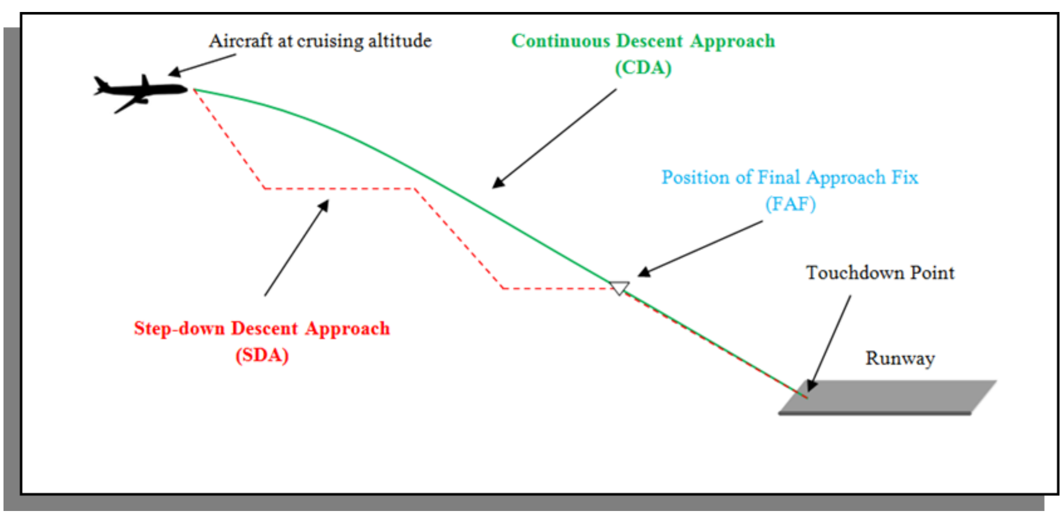

Figure 3.5 The vertical profile of CDA compared with the SDA.

3.3.4 Comparison between CDA and SDA

In this section, we provide a comparison between CDA and SDA from an operational perspective. For example, in case if a pair of aircraft is approaching an airport for landing on the same runway, it is likely that the ATC will increase separation distance between these aircraft when CDA is used, rather than SDA. Numerous studies, such as (Cao et al., 2011b, Robinson and Kamgarpour, 2010b), have pointed that during CDA operations ATC may impose larger separation distance than Non-CDA. This larger spacing for CDA aircraft is mainly due to two reasons; the difficulty for ATC to predict the future position of an aircraft with significantly variable speed (Clarke, 2004), and the inability for pilot to quickly decelerate during descent (Weitz et al., 2005). In fact, the need to increase the separation distance with aircraft flying CDA is one of the major drawbacks of CDA that prevents wide spread of this procedure during busy traffic levels. Although CDA has been proved to be feasible and did not compromise the required spacing between aircraft under light traffic conditions, such as nighttime operations (Clarke, 2004), however, aircraft flying CDA are most likely will be further spaced under heavy traffic condition. Thus, it is a valid assumption that separation distance between aircraft flying CDA would be larger than aircraft flying SDA.

Considering aircraft approach speed, if a pair of aircraft is approaching an airport for landing heading for the same runway, both aircraft approach speed may not be the same when CDA is used, rather than SDA, even with the same aircraft type. This is due to the fact that during descent, pilots make efforts to achieve stabilized approach by controlling and balancing several parameters such as rate of descent, approach speed, thrust, and aircraft's attitude. Since a typical landing is performed operationally with idle thrust, which is conformed with a typical CDA, aircraft approach speed decreases just before touchdown with CDA (FAA, 2015a). On the other hand, with SDA, in which pilot utilize thrust and adjust speed more frequently along the descent path, aircraft approach speed increases just before touchdown.

To summarize, both CDA and SDA operations have advantages and disadvantages. SDA may help ATC expedite traffic during high traffic periods, but it will have adverse impact on populated community in close vicinity of airports with increased noise levels and harmful emissions, while CDA will reduce these environmental impacts, saves fuel, reduce workload on cockpit crew and ATC, it may affect airport arrival rate (AAR) and throughput due to wider separation between aircraft that may imposed by ATC for safety purposes. Table 3.1 summarizes a comparison between CDA and SDA that covers aspects used to highlight the underlying differences between CDA and SDA operations

Table 3.1 Summary of Comparison between CDA and SDA

Comparison Criteria	CDA	SDA
Definition	Aircraft operating technique enabled by airspace design, procedure design and air traffic control (ATC) facilitation, in which an arriving aircraft descent continuously from cruise altitude with idle or near-idle thrust and low drag configuration to final approach fix (FAF) and proceed to the landing runway threshold.	Aircraft operating technique in which arriving aircraft descents from cruise altitude by leveling off in a step-like fashion due to restrictions in airspace and/or air traffic control (ATC) to FAF altitude.
Operational Benefits	Reduces noise, emissions, flight time, and improve fuel efficiency.	May expedite air traffic during periods of high demand at airports.
Facilitation	Tactical ATC vectoring; published arrival procedures (Standard Terminal Arrival Routes "STAR") during busy periods; or a combination of these.	Subject to standard radar vectors from ATC with speed and altitude control.
Approach Type Based on Vertical Navigation	Performance path computed by the flight management system (FMS) using idle or near-idle thrust from top of descent (TOD) point to down to the first waypoint.	Geometric path computed by the flight management system (FMS) from point-to-point between two constrained waypoints.
Preparation and Planning	Requires pre- and in-flight planning in order to achieve optimal profile descent and close coordination with ATC.	Requires pre- and in-flight planning and adherence to ATC instructions in speed and altitude control.
Sequencing and Separation of Air Traffic	May requires more spacing during ATC vectoring and early sequencing (via automated sequencing tools, minimal speed adjustments, point merge, or vectoring) of aircraft to increase the frequency and duration of operations during periods of high traffic density.	Follows separation minima standards based on an appropriate sequencing method for the aircraft fleet mix of aircraft arrivals.
Impact on Airport Capacity, Airport Arrival Rate (AAR), and Air Traffic Operations	May reduce airport capacity, AAR, and lower air traffic operations efficiency during busy periods of traffic volume.	May increase airport capacity and expedite air traffic flow during busy periods of traffic volume.
Aircraft Performance: Altitude	When possible, pilot initiate descent from TOD point as high as possible, preferably, from cruise altitude, and minimize level-offs along the descent profile.	Normally, pilot initiate descent from TOD point at cruise altitude and level-off along the descent profile to altitudes assigned by ATC.
Aircraft Performance: Airspeed	Smooth speed profile, although pilot may make occasional adjustments in speed at ATC request to account for traffic sequencing and separation, and also to balance the rate of descent.	Fluctuating speed profile as pilot make aircraft decelerate before the level-off and accelerate on level at ATC instruction to reach a waypoint or fix and/or expedite air traffic flow.

3.4 CDA Adoptability at Airports

In this section, we present the concept of CDA Adoptability (CDA-A) at airports, which refers to the level of CDA operations an airport can safely and efficiently accommodate and accept per hour. Mathematically, CDA-A is expressed by the CDA Adoptability Factor (CDA-AF), which is the ratio of average arrival hourly rate of CDA operations at an airport, λ_{CDA}, to total aircraft arrival per hour at that airport (i.e., Airport Arrival Rate "*AAR*").

$$\text{CDA-AF} = \frac{\lambda_{CDA}}{AAR} \qquad (3.1)$$

As shown from the formula before, CDA-A is a function of the *AAR*, which prelude to discuss the factors that impact CDA-A in the following section.

3.4.1 Factors Impact CDA Adoptability

There are several factors that may impact the nature of aircraft arrival and approach operations at airports in general, and CDA-A, in particular. Such factors may be operational, meteorological, planning, technological, or related to airspace structure and procedure design. A non-inclusive list of these factors is presented and briefly discussed in the following subsections. While it is important to note that factors, such as technology factors (e.g., level of air traffic management automation at airport) are beyond the scope of this present work, other factors, such as traffic at neighboring airports, wind speed and direction, can be captured by reducing aircraft stacking space and increasing the separation distance between aircraft.

3.4.1.1 Airport Arrival Rate

Principally, arriving traffic at airports is represented by Airport Arrival, or *Acceptance*, Rate (*AAR*). AAR could be defined as the dynamic parameter that specifies the number of arrival aircraft that an airport, in conjunction with terminal maneuvering airspace (TMA), can accept during any consecutive sixty minute period of time (FAA, 2015b). AAR states the hourly capacity for an airport, and thus it is critical to CDA-A. In fact, equation (3.1) shows that AAR is the single, most important factor that influence CDA-A.

3.4.1.2 Arrival Fleet Mix and Separation Requirements

Aircraft fleet mix, or more generally fleet mix, refers to the ratio of various aircraft types that based on wake turbulence categories that make up the total arrival demand operate to an airport. Fleet mix is essential in airport planning to determine the likely average landing speed and separation requirement on final approach, which are important factors affects the AAR, and in turn, CDA-A. Generally speaking, and from the perspective of runway capacity, which is defined as the expected number of landings performed per hour on a runway, a relatively homogenous fleet mix that is consists of one or two dominant aircraft classes is favorable than a heterogeneous fleet mix.

To maintain safety, a specific set of required minimum separations between aircraft flying under instrument flight rules (IFR) is crucial in every ATM system. These separation requirements determine the maximum number of aircraft that can navigate each part of the airspace or can use a runway system per unit of time. The separation requirement for aircraft landing on the same runway specifies the minimum separation in longitudinal distance or time that must maintained at all times between two aircraft operating consecutively on the runway. These requirements are also specified for every possible pair of classes and every possible sequence of movements, (de Neufville et al., 2013). Table 3.2 exhibits the ICAO's minimum wake turbulence separation standards, and apparently, the larger the separation required by ATM system, the lower the AAR, and CDA-A, as well. Furthermore, the more heterogeneous the fleet mix at airport, the more influence will be on AAR and CDA-A.

Table 3.2 ICAO Minimum Wake Turbulence Separation Standards

	Trailing aircraft					
Leading aircraft	Separation in distance (*NM*)			Separation in time (s)		
	Heavy	Medium	Light	Heavy	Medium	Light
Heavy	4	5	6	105	131	158
Medium		3	4		79	105
Light			3			79

3.4.1.3 Wind Speed and Direction

Among the usually considered weather conditions at airports such as cloud ceiling and visibility, wind speed and direction are the most influential conditions on ATM operations, in general, and approach operations, in particular. The two components of wind; head winds (i.e., winds aloft) and tail winds, have significant impact on AAR as well as CDA-A. In fact, wind speed and direction dictates the availability and orientation of runways at any given time. Adverse wind conditions can reduce AAR due to increased complexity of merging arrival traffic streams and separating aircraft as they descend and change heading under intense or varying winds. Specifically, winds aloft may result in a phenomena called compression, in which the separation between pairs of arriving aircraft decreases rapidly as they descend to final approach (DeLaura et al., 2014). Our model will capture the effect of wind speed and direction on CDA adoptability.

3.4.1.4 Airspace Constraints

In general, airport and airspace constraints refer to limitations that hinder airport capacity by creating difficulties for arrival aircraft largely due to airspace consideration. Often, such constraints are contingent on original airspace design that gradually became less efficient due to increasing demand and fluctuating traffic patterns, or airspace redesign that necessitates consideration to nearby restricted airspace. Typically, an airspace redesign process called *sectorization* is performed for inefficient airspace that leads to congestion to architecturally partition it into a number of sectors to improve its capacity and minimize ATC workload (Trandac et al., 2005) (Xue, 2009).

On the other hand, a restricted airspace, which is an area of airspace typically used by the military operations, close to an airport impose a specific airspace design affects arrival aircraft pattern, impact AAR, and influence CDA-A. Other airspace constraints include topographical nature and terrain (e.g., airport close to mountainous terrain). As a factor impact AAR, and in turn, CDA-A, airspace constraints is beyond the scope of this work. While estimating the effect of this factor is beyond the scope of this work, our model is able to capture this effect.

3.4.1.5 Air Traffic at Neighboring Airports

Growth in air traffic at airports with close geographical proximity likely will create congestion, especially if these airports in a large, busy metropolitan area. Such system of airports referred to as *metroplex*, which the Joint Planning and Development Office (JPDO) defines under the Concept of Operations for the Next Generation Air

Transportation System as a group of two or more adjacent airports whose arrival and departure operations are highly interdependent (Joint Planning and Devlopment Office, 2011). Operationally, air traffic flows into and out of airports within a metroplex airport system need to be coordinated between airports to maintain efficient air traffic and individual airports' throughput, with less impact on AAR of airport over another, and therefore impact CDA-A (Ramanujam and Balakrishnan, 2015, Wei et al.).

3.5 Estimation of Aircraft Landing Time at Airports

3.5.1 Using Descent Rules of Thumb

In this section, we provide estimate to the time aircraft takes to descend starting from TOD point at cruise altitude down to the runway, under CDA and SDA operations. The formulas are derived from the descent rules of thumb that are still used by pilots to determine when they need to descend in terms of miles prior the point at which they desire to arrive at a new altitude.

Essentially, the descent rules of thumb are rules from which simple arithmetic operations can be used for descent planning before-flight and updates applied to them by pilots during-flight. Although descent planning and execution could be performed automatically through the Flight Management System (FMS) in a typical passenger aircraft, these rules are still used by pilots as simple and quick technique to manually plan for descent and compare the descent computations generated from the FMS. The descent rules of thumb rely on basic relationship between descent performance variables, such as aircraft speed and altitude needs to be lost, to carry out quick calculations in order to obtain answers for descent planning. Although these calculations does not consider aircraft weight at TOD point, they account for wind effect by adjusting final results based on wind component(s) (i.e., head or tail) acted on aircraft (FAA, 2015a). Figure 3.6 illustrates the descent rules of thumb and the arithmetic expressions associated with them.

The Descent Rules of Thumb

1. **First Rule:** for initial descent planning in jet aircraft flying instrument flight rules (IFR):
    - Use the 3:1 formula—it takes 3 nautical miles to descend 1,000 feet.
2. **Second Rule:** to determine how far to start descending from current altitude to new altitude:
    - Divide the altitude needed to lost by 300, using the following formula:

      New Altitude for Descent = Difference in Altitude ÷ 300
3. **Third Rule:** to determine the Rate of Descent (ROD) for 3-degrees flight path:
    - Multiply ground speed by 5, using the following formula:

      Rate of Descent (ROD) = Ground Speed × 5

Figure 3.6 The descent rules of thumb and their associated arithmetic formulas.

To estimate aircraft landing time, we generally consider the ATC procedure in which ATC clear aircraft for approach with specific altitude and speed instructions, and pilots have to report altitude and speed over the descent flight path as they descend for landing, regardless of type of approach, CDA or SDA. Depending on the cruise altitude at which aircraft will initiate descent, this method of managing descent by ATC could be viewed as a series of altitudes sets the aircraft will dissipate with corresponding speeds when descending. For example, ATC at Portland Approach Center may clear a United 135 flight for approach using phraseology such as "Portland approach, United 135, cleared for approach, level fifteen thousand, descend, and slow to two seven zero knots".

Furthermore, the underlying assumption to estimate aircraft landing time is that aircraft is approaching a congested TMA during the period of high demand at the airport destination.

Relying on the descent rules of thumb, a formula could be developed to computationally estimate aircraft landing time. However, we first estimate the altitude that needs to be dissipated by the aircraft as the difference between the altitude aircraft currently flying at, and the altitude aircraft will descend to, as follows:

$$\Delta h = CA - NA \tag{3.2}$$

where:

Δh = altitude needs to be dissipated by aircraft, in feet, and CA and NA are current and new altitude, respectively.

The point at which pilot should initiate descent is referred to the TOD. The TOD location, in nautical miles, could be estimated by dividing the altitude that the aircraft needs to lose by 300, as follows:

$$\text{TOD} = \frac{\Delta h}{300} \tag{3.3}$$

The rate at which aircraft should descent, or the rate of descent, *ROD*, could be estimated by multiplying ground speed by 5, as follows:

$$ROD = GS \times 5 \tag{3.4}$$

where GS = ground speed, in knots. Generally, the distance that the aircraft covers during descent, in nautical miles, could be estimated by dividing the altitude that needs to be dissipated by speed. This estimation of distance for descent could be done for every descent requirement over the descent profile. However, due to federal regulations that restricts aircraft from flying a speed more than 250 knots below 10,000 feet, then if the aircraft is flying above 10,000 feet, the distance covered over the descent path could be estimated by dividing the altitude that needs to be dissipated by ground speed, as follows:

$$DD = \frac{\Delta h}{GS} \tag{3.5}$$

where DD = distance for descent. On the other hand, if the aircraft is flying at or below 10,000 feet, then the distance covered over the descent path could be estimated by dividing the altitude that needs to be dissipated by approach speed, as follows:

$$DD = \frac{\Delta h}{AS} \tag{3.6}$$

Finally, the time aircraft takes for landing, in minutes, could be generally estimated dividing the distance covered over during descent by speed. Again, depending on whether the aircraft flies above or below 10,000 feet, the speed that should used in the first case will ground speed, while in the later will be approach speed. The total time that an aircraft takes to land will be then the total distance that the aircraft have covered over its descent path divided by the speed that corresponds to the altitude at which it flies.

Using actual data of flights operated to Nashville International Airport (BNA) on June 17th, 2015, that contains various aircraft types with CDA and SDA operations, a computational algorithm was developed to compute landing time for these flights. Further details on this algorithm is provided in Appendix A.

The output of the computational algorithm to estimate landing times for various aircraft types at BNA airport is presented in Figures 3.7 and Figure 3.8. While Figure 3.7 shows the estimated landing time for aircraft with CDA operations, Figure 3.8 shows the estimated landing time for aircraft with SDA operations.

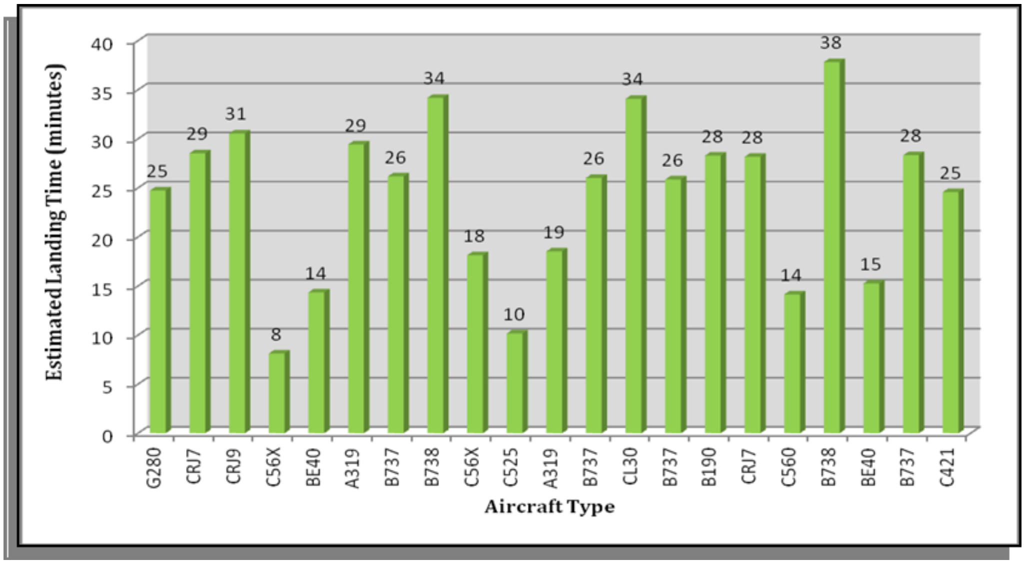

Figure 3.7 Estimated landing times for aircraft with CDA at BNA airport.

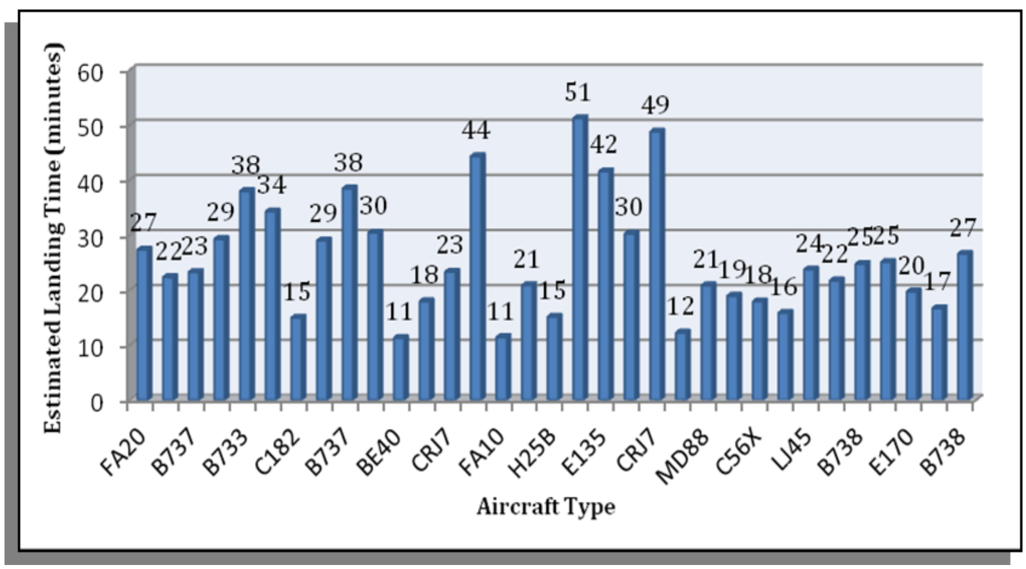

Figure 3.8 Estimated landing times for aircraft with SDA at BNA airport.

3.5.2 Using Base of Aircraft Data (BADA) Aircraft Performance Model (APM)

Base of Aircraft Data (BADA) is an Aircraft Performance Model (APM) developed and maintained by the European Organization for the Safety of Air Navigation, commonly known as EUROCONTROL, through active cooperation with aircraft manufacturers and operating airlines. BADA provides aircraft performance and operations models suitable for trajectory simulation in ATM modeling and simulation tools to validate and assess new ATM concepts, ATC procedures, and advanced ATC Decision Support Systems (DSS) before operationally deployed. BADA also used for trajectory prediction in the ground-based operational ATM systems to better plan traffic flows, reduce delays, and assess aircraft emissions (EUROCONTROL).

Essentially, BADA APM is based on a kinetic approach to aircraft performance modeling. and it consists of two components; the **Model Specifications** that provides the theoretical fundamentals used to calculate the aircraft performance parameters; and the **Datasets** that contains the aircraft-specific coefficients necessary to perform the calculations. To estimate aircraft descent times, a variant of BADA APM, also referred to as family, called BADA Family 3 was used through licensed agreement from EUROCNTORL, as BADA Family 3 represents today's standard for aircraft performance modeling by providing close to 100% coverage of aircraft types used in the European continental airspace, and designed to model aircraft behavior over nominal part of flight envelope and to meet today's requirements for aircraft performance modeling and simulation.

To estimate aircraft landing time at airports using BADA, BADA's web-based Calculation Tool; the Aircraft Performance Calculation (APC), was used to calculate aircraft performance for descent phase of flight. Essentially, APC provides access to online implementation of BADA APM, which consists of database of aircraft operational performance files (OPFs) and formulas derived from the Total-Energy Model (TEM) that EUROCONTROL relied on to model aircraft performance in categories such as aircraft, aerodynamics (e.g., drag), and engine thrust, as shown in the following sections. Further details on BADA APC is provided in Appendix B.

Aircraft Model

For straight-and-level flight at cruise altitude, the aircraft speed is giving by:

$$V_{TAS} = a_o \cdot M_{cruise} \cdot \sqrt{\frac{T}{T_o}} \tag{3.7}$$

where V_{TAS} is aircraft true airspeed (TAS) in nautical miles per hour (knot), a_o is the speed of sound at sea level in knot, M_{cruise} is the Mach at cruise altitude, T and T_o are temperature at cruise altitude and at sea level, respectively.

The lift coefficient, C_L, can be calculated from the classical lift force formula as the product of the dynamic pressure, as follows:

$$L = C_L \frac{1}{2} \rho V^2 S \tag{3.8}$$

where ρ is the density of air in kilograms per meter cubic, V is the aircraft speed in meter per second, and S is the aircraft's wing area in meter squared.

In cruise flight, the lift force, L, in Newton, may assumed to be equal to the aircraft weight in kilograms, m, then:

$$C_L = \frac{2mg}{\rho V^2 S} \tag{3.9}$$

where g is the acceleration due to earth gravity. Assuming no-wind scenario, and the flight path angle in degrees is γ, then the relationship between ground speed and true airspeed is giving by:

$$V_{ground} = V_{TAS} \cdot \cos\gamma \tag{3.10}$$

Drag Model

Drag is the aerodynamic force acting on aircraft body in terms of air resistance to aircraft motion through air. Similarly to the lift force, the aerodynamic drag is the product of the dynamic pressure and drag coefficient, as follows:

$$D = C_D \frac{1}{2} \rho V^2 S \tag{3.11}$$

The drag coefficient is giving by the sum of zero-lift, C_{Do}, and induced drag, C_{Di}, coefficients, where the later is a quadratic function of lift coefficient, as follows:

$$C_D = C_{D_o} + C_{D_i} C_L^2 \tag{3.12}$$

Typically, C_{Do} and C_{Di} are functions of aerodynamic configuration of aircraft flight phase. Generally, drag coefficients are functions of Mach number and Reynolds number ($Re = \rho VL/\mu$ where μ is the absolute viscosity coefficient of air). For each aerodynamic configuration, BADA models these coefficients as constants to provide computations for altitude and speed profile thresholds at pre-determined flight phases (i. e., takeoff, initial climb, clean, approach and landing).

Thrust Model

BADA uses a general formula to calculate the maximum climb and take-off thrust at standard atmosphere for three different types of engines; namely, jet, turboprop, and piston engines. For jet engines, the general equation is given as:

$$Thr_{\max,\text{climb}} = C_{Tc,1} \times \left(1 - \frac{H_p}{C_{Tc,2}} + C_{Tc,3} \times H_p^2\right) \tag{3.13}$$

The descent thrust is then calculated from the maximum climb thrust using adjustment coefficients for cruise, approach and landing configurations (Nuic, 2010) respectively, as follows:

$$Thr_{\text{des,low}} = C_{Tdes,\text{low}} \times Thr_{\max,\text{climb}} \tag{3.14}$$

$$Thr_{\text{des,app}} = C_{Tdes,\text{app}} \times Thr_{\max,\text{climb}} \tag{3.15}$$

$$Thr_{\text{des,ld}} = C_{Tdes,\text{ld}} \times Thr_{\max,\text{climb}} \tag{3.16}$$

where $C_{Tc,1}$, $C_{Tc,2}$, $C_{Tc,3}$, $C_{Tdes,low}$, $C_{Tdes,app}$, and $C_{Tdes,ld}$ are aircraft-specific coefficients, and H_p is the geo-potential pressure altitude, in feet.

The rate, in feet per minute, at which an aircraft's altitude changes with respect to time when descending and approaching the runway for landing is the Rate of Descent (ROD). ROD is giving by:

$$ROD = \frac{dh}{dt} = \frac{(Thr_{des} - D)V_{TAS}}{mg} - \frac{V}{g}\frac{dV}{dt} \tag{3.17}$$

where $\frac{dV}{dt}$ is the aircraft vertical speed, in feet per minute.

The flight path angle in degrees, γ, for a 3-degree flight over the descent path is giving by:

$$\gamma = \sin^{-1}\left(\frac{ROD}{\mathrm{V}_{app}}\right) \tag{3.18}$$

where V_{app} is the aircraft approach speed, in knots.

The distance, in nautical miles, that aircraft cover over the descent path is giving as follows:

$$\text{Distance} = \frac{(\Delta h \div 100)}{\gamma} \tag{3.19}$$

where Δh is the difference between the altitude aircraft currently flying at, and the altitude aircraft will descend to, in feet.

Finally, the time, in seconds, that aircraft takes to land could be estimated by dividing the difference in altitude, by rate of descent, in feet per minutes, as follows:

$$\text{Landing Time} = \frac{\Delta h}{ROD} \tag{3.20}$$

3.5.3 Evaluation of Estimated Landing Times

In this section, evaluation to estimated landing times for CDA and SDA operations is carried out. This evaluation is performed by comparing estimated landing times for CDA and SDA operations using the two methods used; the descent rules of thumb and BADA

APC, against actual landing times with CDA and SDA from actual data of flights operated to BNA airport. However, before we do so, it is important to briefly describe and compare these two methods in terms of complexity, requirement to aircraft weight, and consideration to wind effects in the computations.

Table 3.3 Summary of Comparison between Methods Used to Estimate Aircraft Landing Time

Criteria	Descent Rules of Thumb	BADA APM
Description	Based on arithmetic calculations used by pilots for descent planning during instrument flight rules (IFR) procedures	Based on Base of Aircraft DAta (BADA) Aircraft Performance Model (APM) for aircraft trajectory planning and ATM operations
Level of Complexity	Simple; and relies on basic relationships between descent performance variables to obtain quick answers	Comprehensive; and uses complex aircraft aerodynamic and performance formulas
Aircraft weight Requirement	Aircraft weight is not required to carry out the calculations	Aircraft weight is required to complete the computations
Consideration to Wind Effect	Account for wind effect by adjusting final results based on wind component(s) (e.g., head or tail)	Does not account for wind effect in descent computations

Essentially, the descent rules of thumb are based on arithmetic calculations used by pilots for descent planning during instrument flight rules (IFR) procedures, while BADA APM is based on EUROCONTROL's Base of Aircraft Data Aircraft Performance Model developed for trajectory planning and simulation of ATM operations. The level of complexity significantly varies between these two methods as descent rules of thumb are simple and relies on basic relationships between descent performance variables to obtain quick answers, while BADA APM is comprehensive and uses complex aircraft aerodynamic and performance formulas. In the descent rules of thumb, aircraft weight is not required to carry out the calculations, while aircraft weight is required in BADA APM to complete the computations. Finally, one can account for wind effect in the descent rules of thumb by adjusting final results based on wind component(s) (i.e., head and/or tail), whereas wind effect is not taken into account in descent calculations when using BADA APM. Evaluating the estimated aircraft landing time is essential to our CDA-A model in order to estimate service time; the reciprocal of μ_s . Now, to evaluate the calculations outputs of the two methods, Figure 3.9 shows a comparison between the estimated landing times computed by the computational algorithm based on the descent rules of thumb, and actual landing times for aircraft with CDA operated to BNA airport.

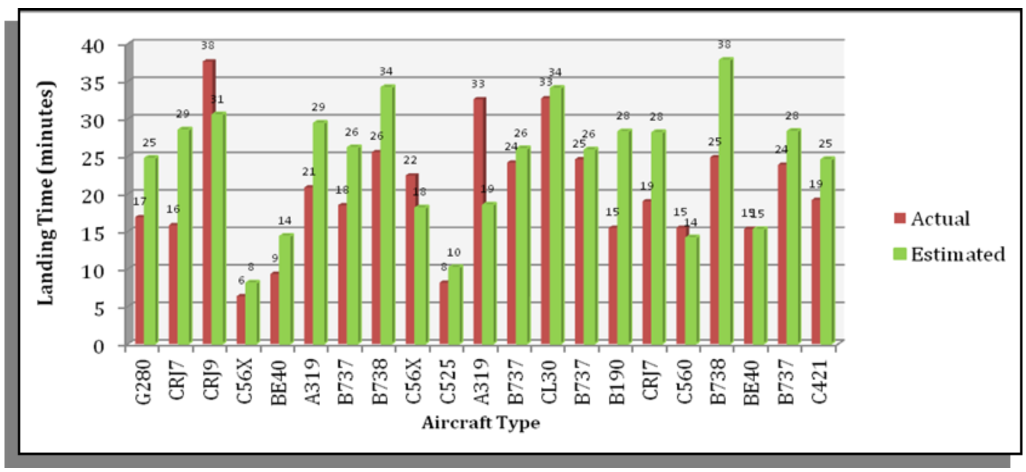

Figure 3.9 Evaluation of landing times for aircraft with CDA at BNA airport estimated using the descent rules of thumb.

Due to variations in aircraft types, performance capabilities, and descent requirements within actual CDA instances, variation is observed in estimated landing times when compared with actual landing times. For example, with B738 aircraft that has estimated and actual landing times of 34 minutes and 26 minutes, respectively; there is an error of 30.7%, while for aircraft B737 with estimated and actual landing times of 26 and

25, respectively; an error of 4%. On average, the computational algorithm based on the descent rules of thumb have estimated landing time for aircraft with CDA operations at 24 minutes. When compared with the actual average landing time for aircraft with CDA at BNA airport, which is 21 minutes, an error of 14.3% was found in this estimation.

Similarly, Figure 3.10 shows a comparison between the estimated landing times computed by the computational algorithm, and actual landing times for aircraft with SDA operated to BNA airport. It shows that for a B733 aircraft with estimated and actual landing times of 38 minutes and 25 minutes; respectively, the algorithm produced an error around 53%, while an error of 39.5% for a CRJ7 with estimated and actual landing times of 23 minutes and 39 minutes, respectively. However, there are SDA instances where the computational algorithm was able to match the estimated landing time with actual landing time, such as with the two cases with H25B aircraft, and the FA50 aircraft. Again, the variation in aircraft types, performance capabilities, and descent requirements within actual SDA cases result in variation in estimating landing times. On average, the computational algorithm based on the descent rules of thumb have estimated landing time for aircraft with SDA operations at 27 minutes. When compared with the actual average landing time for aircraft with SDA at BNA airport, which is 24 minutes, an error of 12.5% was reported from this estimation.

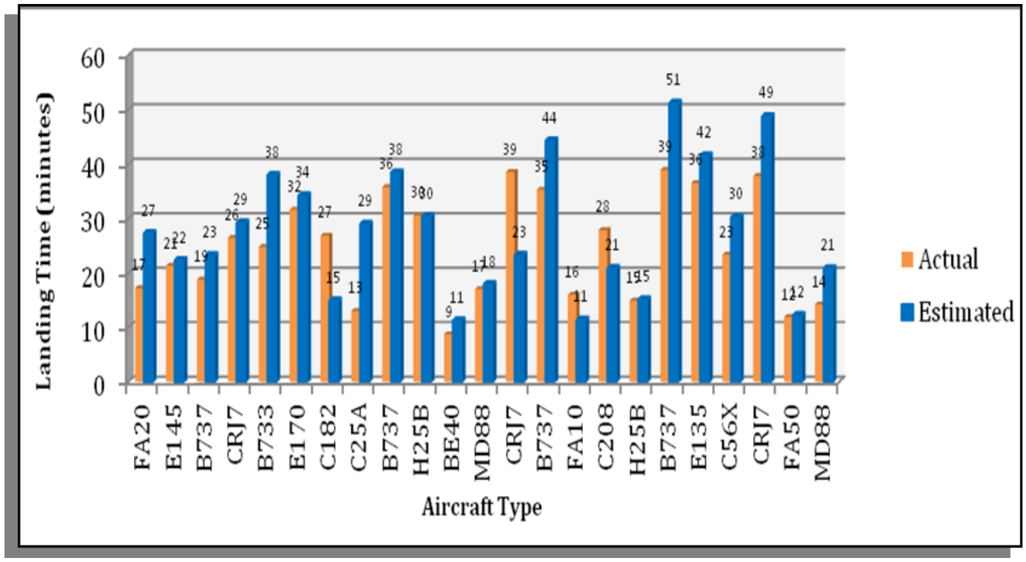

Figure 3.10 Evaluation of landing times for aircraft with SDA at BNA airport estimated using the descent rules of thumb.

On the other hand, to evaluate the calculations outputs of BADA APM, Figure 3.11 shows a comparison between the estimated landing times computed by BADA APC, and actual landing times for aircraft with CDA operated to BNA airport. Across the compared values, and generally speaking, slight variation is observed between estimated landing times and actual landing times. For example, with CRJ9 aircraft that has estimated and actual landing times of 38 minutes and 27 minutes, respectively; there is an error of almost 29%, while for aircraft CRJ7 with estimated and actual landing times of 20 and 19, respectively; an error of 5.3%. On average, BADA APM have estimated landing time for aircraft with CDA operations at 20 minutes. When compared with the actual average landing time for aircraft with CDA at BNA airport, which is 21 minutes, an error of 4.7% was generated from this estimation.

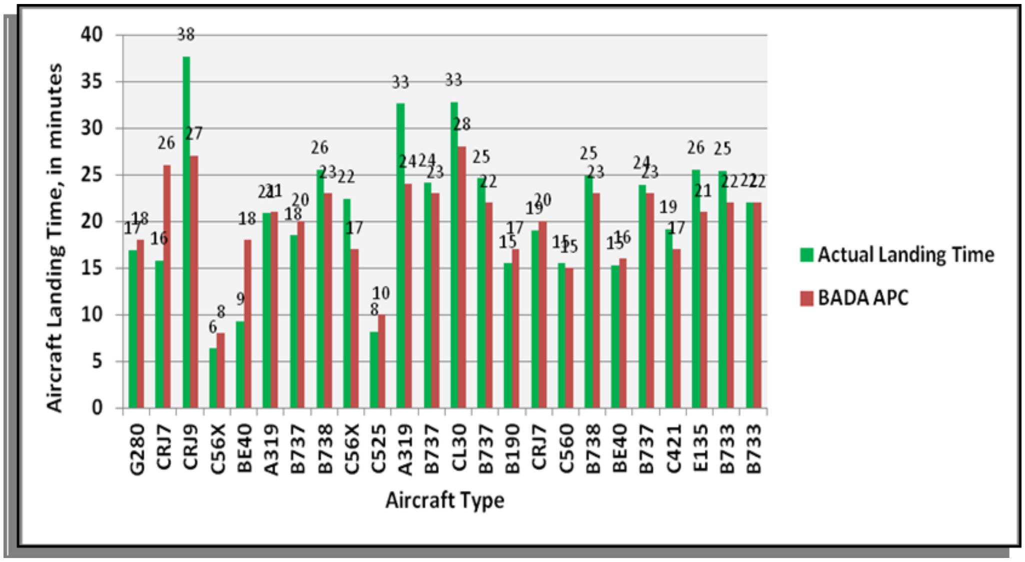

Figure 3.11 Evaluation of landing times for aircraft with CDA at BNA airport estimated using BADA APC.

Similarly, Figure 3.12 shows a comparison between the estimated landing times computed by BADA APM using BADA APC, and actual landing times for aircraft with SDA operated to BNA airport. It shows that for a B737 aircraft with estimated and actual landing times of 32 minutes and 36 minutes; respectively, BADA APC produced an error around 11%, while an error around 8% for a E135 with estimated and actual landing times of 39 minutes and 36 minutes, respectively. However, there are SDA instances where BADA APC was able to match the estimated landing time with actual landing time, such as with MD88 aircraft, or close to match, such as with the FA50 aircraft. On average, BADA APC have estimated landing time for aircraft with SDA operations at 21.7 minutes. When compared with the actual average landing time for aircraft with SDA at BNA airport, which is 24 minutes, an error of 9.6% was reported from this estimation.

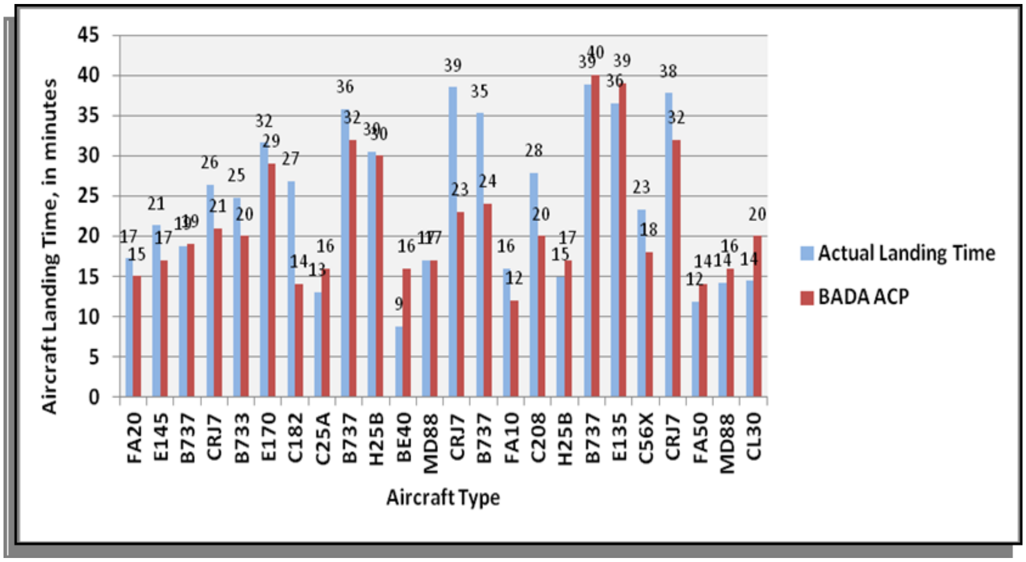

Figure 3.12 Evaluation of landing times for aircraft with SDA at BNA airport estimated using BADA APC.

Finally, Table 3.3 summarize the evulation of the two methods used to estimate aircraft landing times, while Figure 3.13 compares the computational accuracy of the algorithm developed based on descent rules of thumb and BADA APC against the actual flight data operated to BNA airport. Finally, it is important to note that aircraft landing time is one of the major parameters needed for our CDA-A model.

Table 3.4 Summary of Evaluation of Methods Used to Estimate Aircraft Landing Time

		Average Landing Time (minutes)					
		Descent Rules of Thumb			**BADA APM**		
		Estimated	Actual	Error (%)	Estimated	Actual	Error (%)
Descent Profile	CDA	24	21	14.3	20	21	4.7
	SDA	27	24	12.5	21.7	24	9.6

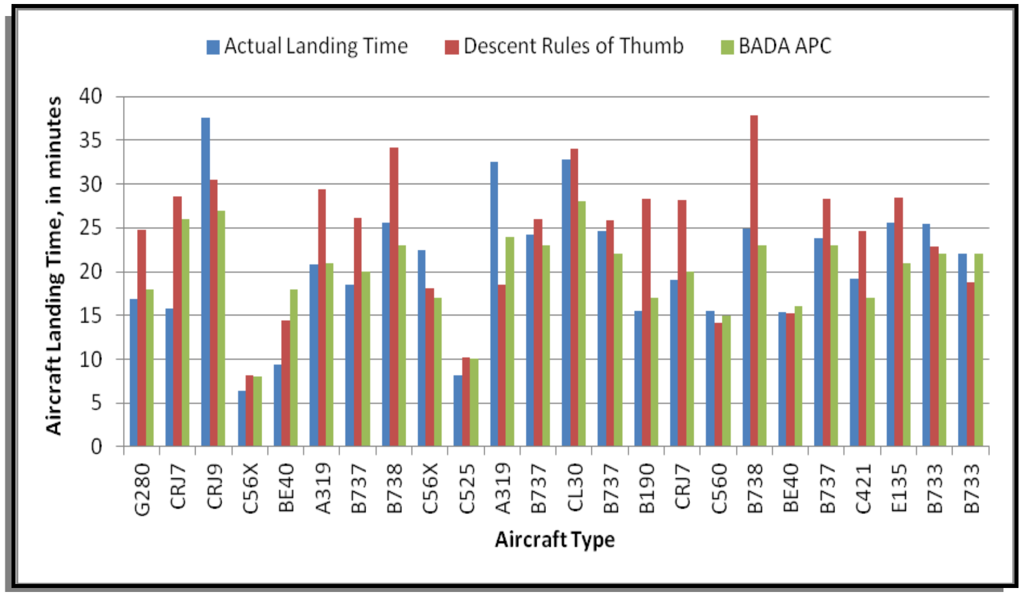

Figure 3.13 Evaluation of methods used to estimate aircraft landing time.

CHAPTER 4

CDA ADOPTABILITY: MODEL AND APPLICATION

This chapter presents the necessary model to provide the thresholds that impact the adoption of CDA. The chapter is organized as follows: after introducing the parameters that governs CDA, such as the terminal maneuvering area (TMA), aircraft wake turbulence class, wind speed, and wind direction. Then the provided approach to capture a single parameter to define a threshold of adopting CDA beyond which it becomes unsafe to apply. Based on this approach, two probabilities will be captured and presented; the first defines CDA threshold, while the second defines the upper bound. Our comprehensive analysis exhibited that the aforementioned parameters can be captured in one measure, which we distinguish as the Probability of Blocking.

4.1 Development of the Model

As previously mentioned, Continuous Descent Approach (CDA) is a flight technique in which aircraft approaching airport descent continuously from cruise altitude to landing with idle engines. In essence, CDA is designed to keep aircraft higher for longer at lower thrust by eliminating the level segments in the traditional step-down approach; thereby reducing fuel burn, noise levels, emissions rates, and flight time. CDA has been successfully adopted in several major airports around the world during light to medium traffic periods; however, the negative impact that CDA could impose on airport capacity have challenged the implementation of this procedure during the heavy traffic of busy periods due to safety concerns that requires increased longitudinal separation for aircraft landing on the runway (Reynolds et al., 2005, Cao et al., 2013, Der Eijk et al., 2012, Tong et al., 2007). Therefore, developing a model that enables airports to adopt more CDA operations during heavy traffic is very important endeavor.

Basically, implementing CDA operations during high traffic at airports is a challenging task. Since the fundamental objective of a controller is guarding safety, then immediately followed by considering efficiency, while other objectives such as noise reduction, fuel and time saving, and passenger comfort are follow; the chances for adopting more CDA operations during high traffic are reduced. This is due to the increased workload on controller as traffic increases, which makes controllers consider less variables for each aircraft as they manage the traffic. When implementing CDA operations under such condition, controllers' workload even increases since each aircraft has to fly its specific optimum descent profile. During this descent, no interventions in terms of speed instructions and/or vectoring should be provided to cockpit crew that would potentially interrupt the CDA. Accordingly, with CDA, the controller should be able to predict the performance of each aircraft over the descent profile as they sequenced for arrival and landing while resolving conflicts before aircraft start the CDA. It can therefore be noticed that the task of controllers become exceptionally complex as the level of traffic increases and the need for more CDA operations adoption.

Nevertheless, the calls for more adoption to CDA operations remains the main objective of civil aviation stakeholders. As such, since the enactment of the FAA's Next Generation Air Transportation System (NextGen) program under the VISION 100 - Century of Aviation Reauthorization Act in 2003 (Gawdiak et al., 2009), CDA has been increasingly attracting researchers' attention. This is clearly noticed in terms of the thrust areas, volume, and diversity of works in literature dedicated to study CDA. Researchers have tackled issues related to CDA implementation from wide range and various aspects, such as benefits assessment and quantification of CDA (Wubben and Busink, 2000, Wilson and Hafner, 2005, Dinges, 2007, Enis T. Turgut et al., 2009), conflict detection and resolution strategies (Shresta et al., 2009), navigation and CDA-enabled routes (Tong et al., 2003), redesign of airspace structure for CDA (Kapp et al., 2012), and merging and spacing of aircraft with CDA (Weitz et al., 2005), to name a few. After extensive survey to CDA literature, Figure 4.1 illustrates main thrust areas in CDA research with some examples of scope of study to factors affects CDA implementation. However, it is worth to note that the scope of this work falls under airport operations research area.

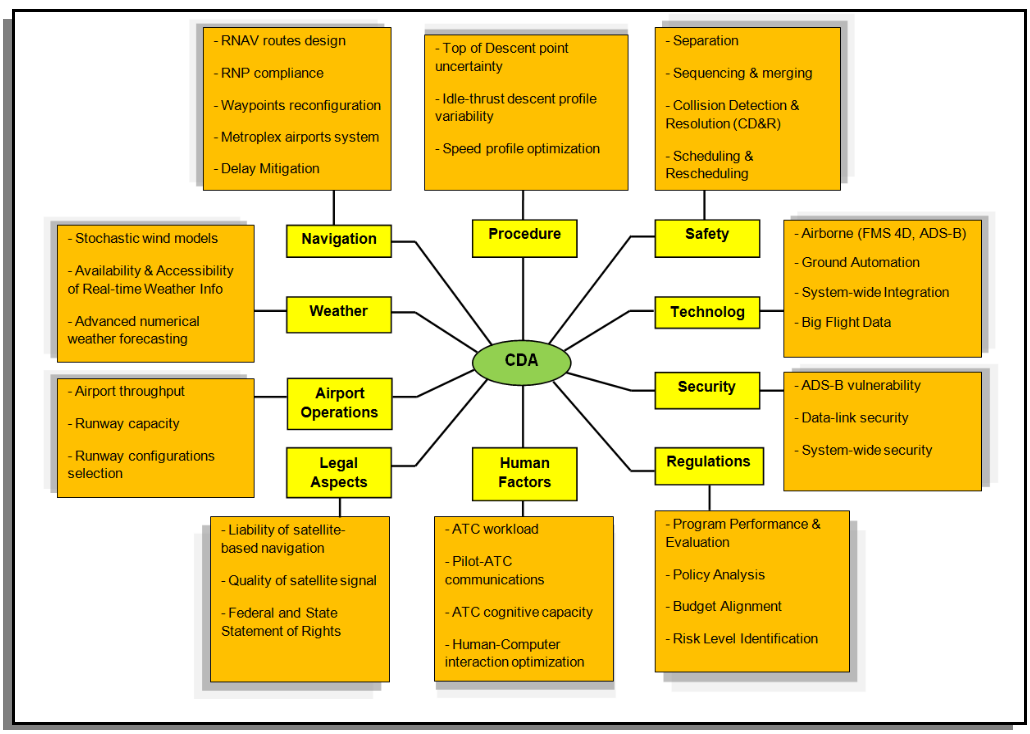

Figure 4.1 Factors affects CDA implementation in main research areas of CDA.

With the promising benefits that could significantly improve air transportation industry on environmental, economic, and operational aspects, extensive research efforts have been dedicated to support and facilitate CDA implementation at airports during normal operating hours, under conflicting factors, without compromising safety over benefits. The significance of this thesis is in the following two-fold focus: "What guidelines or metrics that could help controllers at the time of decision making identify the potential extent of CDA implementation and make informed decisions on CDA adoptability?", and "What could be a better approach that would help controllers, safely and efficiently, manage CDA operations for more CDA adoptability during high traffic periods in order to improve flow in terminal maneuvering area (TMA) airspace, given the operational nature of CDA operations?". For the prior focus, several studies (Stibor and Nyberg, 2009, Novak et al., 2009, Gągorowski, 2012, Clarke et al., 2013) have recommended developing guidelines or metrics capable of expressing merits and need to taken for complete CDA implementation that include the high level of traffic. However, little attention has been given to study factors that affects CDA implementation and limits the level of gain of its benefits with scope to characteristics related to airports. Although such factors may be acknowledged and identified in literature, but to our knowledge, there is not enough work has been devoted to specifically study the interaction amongst them that affects CDA and present metrics or guidelines for more CDA implementation and adoption.

The second focus, on the other hand, still has a lot of work and approaches in literature did not sufficiently address. Although innovative operational concepts drawing from machine learning to predict flights' estimated time of arrival (ETA) at airports with improved accuracy using Random Forest (RF) (Kern et al., 2015); as well as in trajectory prediction research that uses machine learning approach to address the challenges of rapidly congested TMA considering aircraft trajectory variability (Ayhan and Samet, 2016). However, sufficient attention has not been given to explicitly consider CDA as the main of focus in their work. Acknowledging the significance of CDA's environmental and operational benefits, this leads to the need to work that mainly focus on CDA using data-driven system approach and predictive analytics to provide a better approach to assist controllers for enhanced CDA Adoptability. The two aforementioned focuses are the motivation for this dissertation.

In summary, the first component of this work aims to address the issue of adopting more CDA operations during periods of high traffic at airports by developing quantitative measure to determine the maximum traffic level beyond which CDA implementation is unsafe, while the second component aims to address the issue of assisting controllers for more CDA Adoptability, taking into account number of factors specific to airports and has direct impact on CDA implementation. To achieve these aims, two models and a framework are presented. The first model, which forms the first component of this work and the core of this chapter, is generally adopted from queuing theory, and validated with numerical examples. Chapter 5 of this dissertation focuses on the second component which develops a framework adopted from data-driven system approach and coupled with machine learning algorithms to build a CDA predictive model. The details of the first model are explained in the following subsections.

4.2 Assumptions and Parameters of the Model

The first model takes into consideration two important assumptions, which are: the space available for stacking aircraft arrivals in the TMA is considered as a server that provide service in the form of CDA operations, and the separation distance between aircraft conducting CDA are greater than the distance between aircraft not conducting CDA.

4.2.1 Capacity of Stacking Space for Aircraft Arrivals

As previously mentioned, CDA is a flight technique in which aircraft approaching airport descent continuously from cruise altitude to landing with idle engines. In essence, CDA is designed to keep aircraft higher for longer at lower thrust by eliminating the level segments in the traditional step-down approach; thereby reducing fuel burn, noise levels, emissions rates, and flight time. CDA has been successfully adopted in several major airports around the world during light to medium traffic periods; however, the negative impact that CDA could impose on airport capacity have challenged the implementation of this procedure during the heavy traffic of busy periods due to safety concerns that requires increased longitudinal separation for aircraft landing on the same runway.

To maximize airport capacity, especially during periods of high demand, air traffic controllers (ATC) stack arriving aircraft for landing in a predetermined airspace according to a predefined requirement for separation between aircraft that typically operating under Instrument Flight Rules (IFR). Numerous studies, such as (Cao et al., 2011b, Robinson and Kamgarpour, 2010b), have pointed that during CDA operations ATC may impose larger separation distance than Non-CDA. This larger separation for aircraft flying CDA is mainly due to two reasons; the difficulty for ATC to predict the future position of an aircraft with significantly variable speed (Clarke, 2004), and the inability for pilot to quickly decelerate during descent (Weitz et al., 2005). In fact, the need to increase the separation distance with aircraft flying CDA is one of the major drawbacks of CDA that prevents wide spread of this procedure during busy traffic periods.

Conceptually, our model considers the aircraft arrivals at an airport during the daytime busy period of a typical operational day. The rate of aircraft arrivals assumed to be random over the period of time considered. Moreover, the fleet mix assumed to be homogeneous; that is, dominated by one or two aircraft wake turbulence classes. The following parameter represents the fundamental components of our model; the space available to stack aircraft arrivals, the minimum allowable horizontal separation distance between a pair of two consecutive same-weight-class aircraft arrivals, and the number of aircraft that could be stacked for approach. Figure 4.2 below illustrates these components in our model.

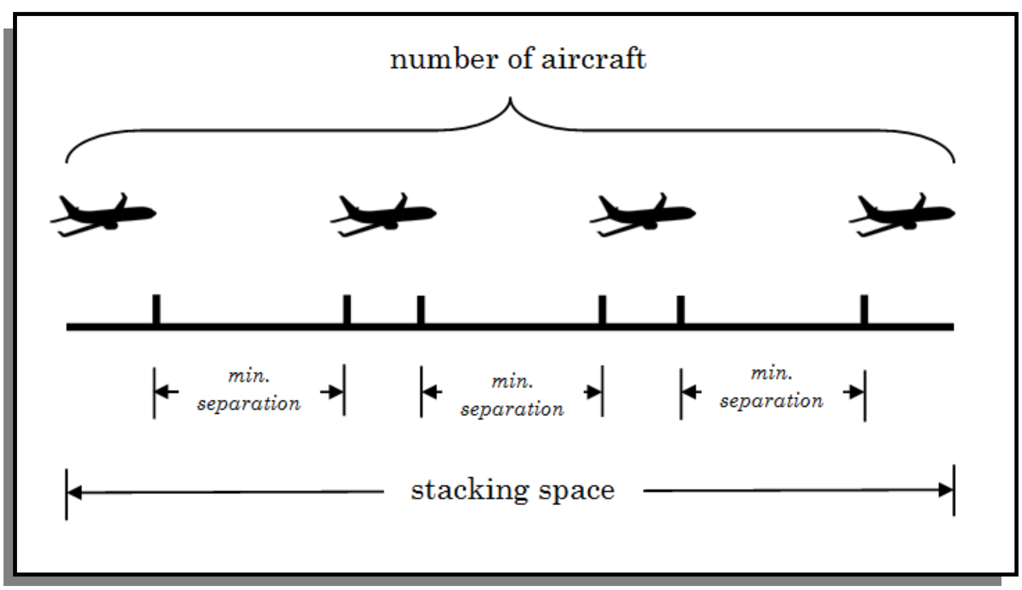

Figure 4.2 The parameters of our model for aircraft approaching airports with CDA.

Before we define the parameters of our model, it is worth to note that during CDA operations, optimal spacing between aircraft is important much important than optimal sequencing (Chen and Solak, 2015). Thus, we principally assume that the horizontal separation distance between two, same-weight-class, consecutive arriving aircraft conducting CDA is *greater* than when these two consecutive arriving aircraft are not conducting CDA, that is:

$$d_{CDA} > d_{Non-CDA} \tag{4.1}$$

where:

d_{CDA} = separation distance between aircraft conducting CDA; and

$d_{Non-CDA}$ = separation distance between aircraft not conducting CDA.

Let the space available to stack aircraft arrivals at airport is S_p, and the minimum allowable horizontal separation distance between a pair of same-weight-class aircraft arrivals is d, then the number of aircraft stacked for approach, k, is estimated as:

$$k \leq \frac{S_p}{d} \tag{4.2}$$

Also, let the aircraft approach speed, measured in knots, on average, is V_{app}, and the distance aircraft covers during descent from Top of Descent (TOD) to touchdown, measured in nautical miles, is D_{des}, then the time that aircraft takes to descent, t_{des}, could be estimated as:

$$t_{des} = \frac{D_{des}}{V_{app}} \tag{4.3}$$

Since implementing CDA during high level of traffic may affect airport capacity as a result of larger horizontal separation distance between aircraft arrivals for safety considerations, and therefore, it requires a balance to be struck between airport capacity, demand, and the need to implement CDA; then we assume that airport capacity, AAR, should be greater than or equal the estimated number of aircraft available in the system. This assumption is represented as follows:

$$AAR \geq \frac{k}{t_{des}} \tag{4.4}$$

Essentially, stacking space is a contained airspace with predefined boundaries based on traffic and/or obstacles limitations with purpose to stack aircraft arrivals at certain capacity. As the separation distance between aircraft increases, stacking space capacity in terms of number of aircraft that could stacked will decreases. Moreover, as airport arrival rate (AAR) increases, typically during periods high of demand, stacking space capacity will decrease, as well.

Finally, it is assumed that almost all aircraft arrivals at airport are expected to successfully land on a runway, regardless of their descent profile type. To attain this operationally, the runway, as a critical element in ATM and airports operations, assumed to have an arrival capacity *larger* than the *AAR*. The maximum runway arrival hourly capacity is calculated by dividing the average aircraft ground speed, in knots, crossing the runway threshold by the separation distance, in nautical miles, required between successive arrivals (FAA, 2015b), as follows:

$$RwyCap = \frac{GS}{d} \tag{4.5}$$

4.2.2 Level of Demand at TMA

Generally speaking, the Level of Demand (LoD) at terminal maneuvering area (TMA) represents the volume of aircraft arrival and departure an airport could safely and efficiently handle during normal operating hours. In this work, LoD is the number of arrival movements that airlines will actually operate during an hour, which is not necessarily the same as total number of aircraft arrivals scheduled per hour. LoD for landing at TMA is tied directly to capacity of stacking space, runway, and airport, as a whole system. Hence, below a certain LoD, controllers can authorize CDAs, as the LoD at TMA increases, however, it becomes progressively more difficult for controllers to allow CDAs because of interference with other traffic flows in TMA. As the LoD approaches capacity, the tradeoff between total airport throughput and individual flight profile efficiency would most likely prevent CDAs at very high traffic density conditions. Implementing CDAs at this level of traffic density would have important environmental and operational benefits without increase in TMA congestion or delay generation.

Considering the stacking space as a service facility that provides CDA as a service to arrival aircraft, significant delays may occur when the demand rate is less than but close to the service rate. Such delays are due primarily the variability of the time intervals between consecutive requests for landing using CDA, as well as due to the variability of the time it takes to *serve* each CDA landing. Typically, LoD for landing reaches its highest level during peak hours of operation at airports, which are normally occurs onto two periods; morning peak that lasts for an hour or two; and afternoon peak which lasts for several hours in a row (de Neufville et al., 2013). Figure 4.3 illustrates LoD fluctuating levels over the hour of the day and the two peak periods for three US international airports; Atlanta's Hartsfield-Jackson (ATL), Denver (DEN), and Albuquerque (ABQ). Early before the current technology advancement in ATM operations, queuing theory has been utilized to study aircraft landing and yet presented viable solutions (Rue and Rosenshine, 1985). As the technology evolves and massive ATM modernization programs, such the FAA's NextGen, and the introduction of new technologies and development of advanced procedures, there has been much work on aircraft descent operation utilizing queuing models to mitigate delays under trajectory-based operations (TBO) (Nikoleris and Hansen, 2012, Nikoleris and Hansen, 2009). However, there was no clear consideration to CDA operations.

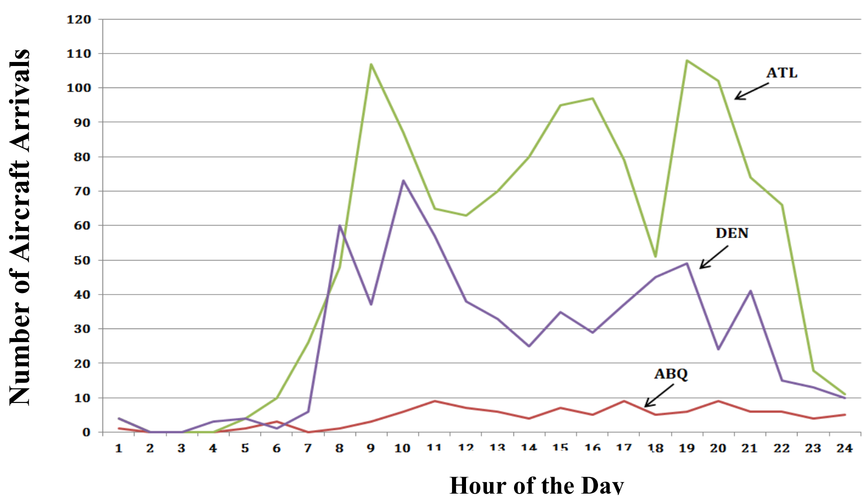

Figure 4.3 The Level of Demand (LoD) over the day at US three international airports
Data Source: FAA's Aviation System Performance Metrics (ASPM) Database (April 17th, 2013)

Perhaps the idea of considering a queuing framework for CDA operations and viewing CDA as a service that could be provided to aircraft arrivals by airports operators could be found in literature in (Alharbi and Abdel-Malek, 2015). Inspired by the aforementioned study, the present work draws from queuing theory to model CDA operations, considering aircraft arrivals for landing as customers, and the stacking space to stack these aircraft as the server. By analyzing and fitting a sample data of flights operated to Nashville International Airport (BNA) airport, the inter-arrival time for aircraft to their Top of Descent (TOD) point found to clearly exhibits exponential probability distribution, as shown in Figure 4.4. Therefore, we consider the aircraft arrivals process follows a Poisson process, which is in line with assumption adapted in other studies in the literature (Chen and Solak, 2015).

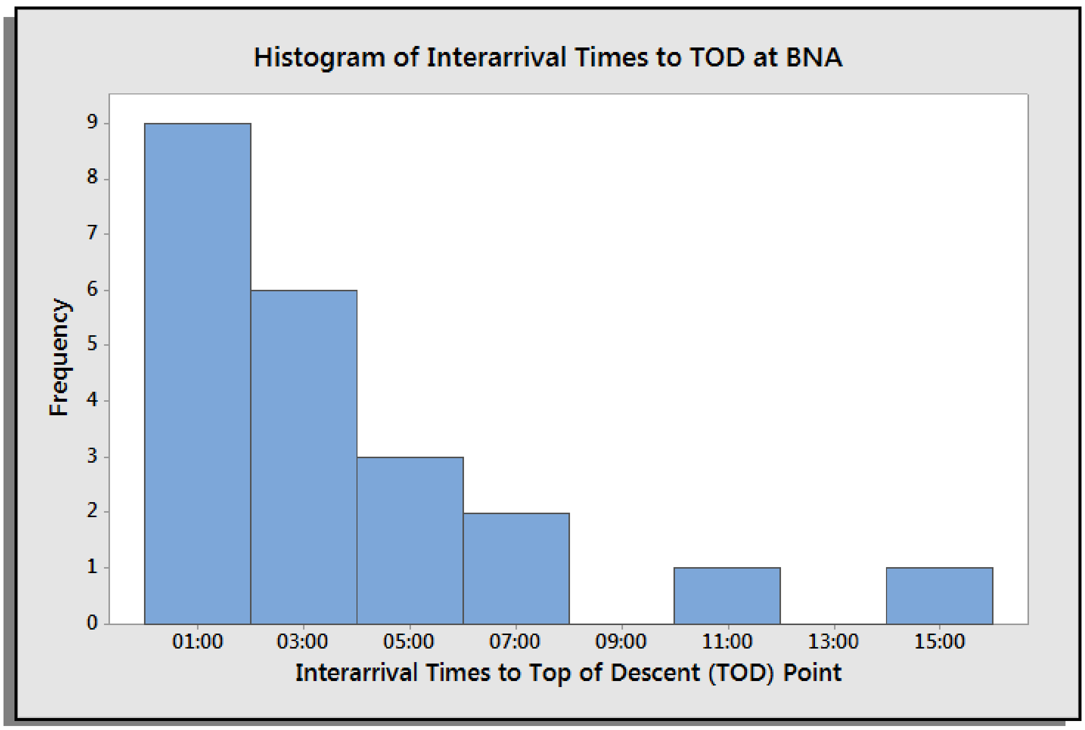

Figure 4.4 Inter-arrival times of sample data of flights operated to BNA airport.

4.2.3 Level of Service at TMA

The Level of Service (LoS) at the Terminal Maneuvering Area (TMA) represents the degree of efficiency in which aircraft arrivals are being processed and *served* for landing. Hence, LoS also indicates the capacity of the stacking space, and how well this capacity is being utilized. As previously presented and discussed in Chapter 3, estimates for aircraft landing time under both CDA and SDA operations has been developed to provide the basis for queuing models that will then determine the probability of blocking. Essentially, these estimates of aircraft landing times forms estimate to the service time for aircraft within the TMA. In our model, we assume this service to be Markovian service process with Markovian service time. Besides it provides conservative estimates, this assumption also provides an upper bound to service time.

4.3 The CDA Adoptability Model

This section addresses the core of this chapter, which is the development of the first model that aim to tackle the problem of CDA adoptability during high traffic periods. The model can be implemented to determine the parameter that defines a threshold beyond which CDA implementation would be unsafe.

4.3.1 Traffic Intensity

As balance is needed between LoD and LoS for TMA at busy airports in order to accommodate more CDA operations during high traffic periods, the queuing theory presents a key parameter known as the traffic intensity, also referred to as the utilization factor, and denoted by the Greek letter ρ_l ("rho"), which is defined here as the average hourly demand rate of the TMA divided by the average hourly capacity (or service) of the TMA. If the average demand rate is denoted by λ_s, and the average service rate is denoted by μ_s, then the utilization factor, ρ_l, for TMA is as follows:

$$\rho_l = \frac{\lambda_s}{\mu_s} \tag{4.6}$$

where demand rate is expressed in terms of aircraft arrival rate, which is typically the airport arrival rate, AAR; and service rate is expressed in terms of the reciprocal of the time aircraft takes, on average, to descend and land on runway, which is typically the time aircraft takes to land estimated in Chapter 3 for CDA and SDA operations.

4.3.2 Probability of Blocking

Based on our fundamental assumption that aircraft descending with CDA requires more separation distance than the traditional SDA, which is in fact one of the main reason that limits CDA implementation during high traffic as it affects airport throughput, this interpreted as it is highly probable that level of CDA operations would be decreased as traffic level increases. In other words, CDA may not be possible all the time, especially during high traffic periods; may not possible for all arriving aircraft, especially with highly heterogeneous fleet mix; and may not always possible for the whole descent profile, since air traffic controller (ATC) can choose to abort a CDA at any time, mainly for safety considerations, and revert to a conventional SDA. Therefore, a crucial measure related to airport operations and TMA as a system needs to be developed to address this issue in order to adopt CDA to the safe and possible extent, and then gradually increase

CDA Adoptability. In this work, we characterize this measure as the Probability of Blocking.

Definition: The Probability of Blocking is the fraction of time an aircraft's request to embark on CDA is denied principally due to safety and because the stacking space within the TMA is busy and congested. This probability is denoted by P_k and could be specified for an airport and its TMA to define a threshold beyond which CDA is unsafe to implement. The Probability of Blocking is expressed based on the *M/M/1/k* queuing model in which the arrival process is Poisson with rate λ_s, service process is Poisson with rate μ_s, a single server (that is, the stacking space), and finite system capacity at k aircraft, as follows:

$$P_k = \frac{1-\rho_l}{1-\rho_l^{k+1}}\rho_l^{k} \tag{4.7}$$

4.4 Model Application

In this section, the proposed model for CDA Adoptability (CDA-A) is implemented through a numerical example using simulated data of the model parameters and the implementation steps are explained in detail. The CDA-A is then validated using actual flight and weather data. Model refinement is performed by carrying out sensitivity analysis to the parameters considered in the model development process; namely, the airport arrival rate, *AAR*; size of the stacking space used to stack aircraft arrivals, S_p; separation distance between aircraft arrivals, d; wind speed, W_s; aircraft approach speed,

V_{app}; and with output as the probability of blocking, P_k. The CDA Adoptability model development process is illustrated in Figure 4.5.

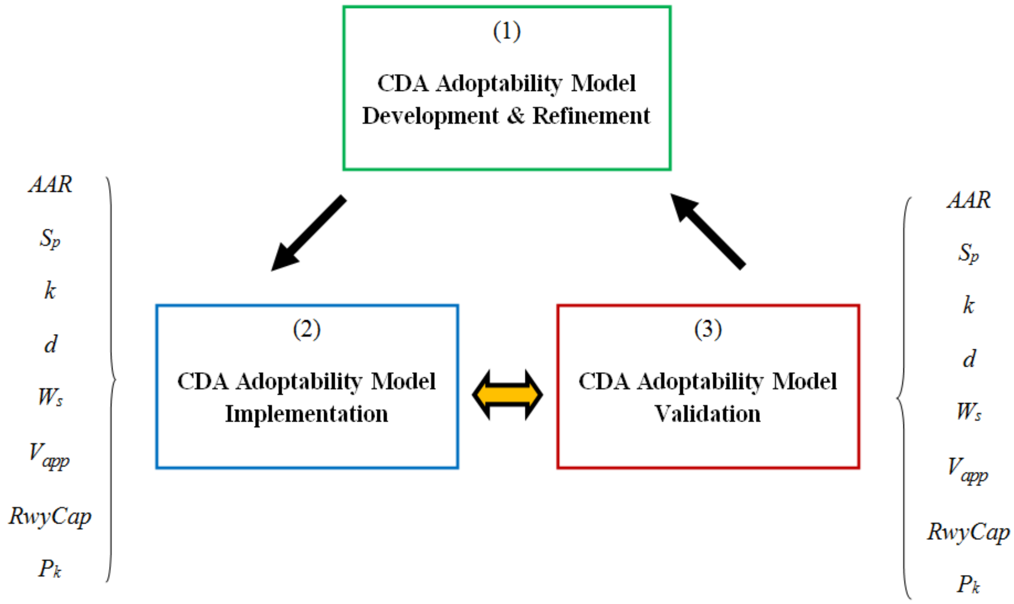

Figure 4.5 The CDA Adoptability model development process.

Consider the scenario where a stream of aircraft arrives for landing at a mid-sized international airport during an afternoon busy level of demand, typically between 1200 and 1700 local time. Because of the tangible environmental and operational benefits of CDA in terms of reducing emissions, noise, and more streamlined operations through flight time reduction; air traffic controllers (ATC) would like to accommodate more CDA operations during this busy period. A number of parameters that have direct influence on CDA adoptability are identified and listed in Table 4.1. Moreover, due to the fact that these parameters are changing over this period of busy operational time, ATC—based on design standards, practical experience and study of patterns from historical data—

provided ranges over which the values of these parameter would take. For instance, V_{app} range were defined based on airport design standards, which are based on aircraft type, wing span, and MTOW (FAA, 2016). The ranges are shown in Table 4.1.

Table 4.1 Summary of Ranges of Values for Parameters

Parameter	Min value	Max value
Airport Arrival Rate, *AAR* (aircraft per hour)	15	18
Size of the stacking space used to stack aircraft arrivals, S_p (nmi)	13	16
Separation distance between aircraft arrivals, *d* (nmi)	3	6
Wind speed, W_s (mph)	1	5
Aircraft approach speed, V_{app} (knots)	128	152

From operational perspective, if an aircraft started to approach an airport from TOD point with CDA, and the CDA did not complete over the whole entire descent profile, then the CDA has been aborted and reverted to SDA. On the other hand, if an aircraft started to approach an airport from TOD point with SDA, however, it is usually uncommon that the aircraft will return to a CDA. In other words, if CDA has been initiated at the TOD point, and for safety considerations it has been terminated over the descent profile and before landing, aircraft will conduct a SDA instead. But if SDA has been at TOD point, it is unlikely that the aircraft will regain a CDA. Therefore, in order to implement our CDA-A model, two probabilities of blocking then should be calculated for each type of descent profile, namely; CDA and SDA, denoted $P_{k_{CDA}}$ and $P_{k_{SDA}}$, respectively. As previously mentioned, probability of blocking is defined as the fraction of time an aircraft request to embark on CDA is denied for safety considerations and due to the stacking space being congested and busy. Without loss of generality, when probability of blocking coined with SDA, it still indicates that the aircraft request for CDA has been denied, or terminated during descent, yet implies that aircraft has mutated to SDA. Furthermore, the behavior of the parameters considered in building the CDA-A model is expected to be as follows: as the *AAR*, *d, W_s*, V_{app} and *k* increase, the P_k would accordingly increase. This behavior is anticipated as simulated data is applied to the CDA-A model, but most importantly, however, it is required to see this behavior match the results when the CDA-A model is validated using actual flight data.

As shown in Figure 4.6, the CDA-A model has been applied using the previously defined parameters on simulated data, and $P_{k_{CDA}}$ and $P_{k_{SDA}}$ has been calculated. $P_{k_{CDA}}$ has reached high values more than once, at *AAR* of 16 and 15 aircraft per hour. Values randomly assigned to *AAR* on *x*-axis to mimic fluctuation of demand at high levels of traffic over a busy period of operation at an airport. For instance, $P_{k_{CDA}}$ was 0.07334 (its highest value during the simulation), 0.05189, and 0.05756, all at *AAR* of 15 aircraft per hour. This indicates that at that *AAR*, aircraft arrivals with requests to conduct CDA will likely be denied. It is shown, however, that at that *AAR*, $P_{k_{SDA}}$ has low values that almost near zero. This indicates that as aircraft request to conduct CDA at the *AAR*, it is unlikely that these aircraft will revert to SDA from CDA; that is, they may not initiate their descent as CDA and then revert to SDA, but rather they will start as SDA. Furthermore, the lines of $P_{k_{CDA}}$ and $P_{k_{SDA}}$ intersects at an *AAR* of 18 aircraft per hour, not only creating an almost equal value of 0.01345, but also a critical point. This means that particularly at that *AAR*, it is likely that aircraft arrivals requesting to conduct CDA will have their requests granted, and at the same time, these it is likely for these aircraft, at some point over their descent profile, to revert SDA.

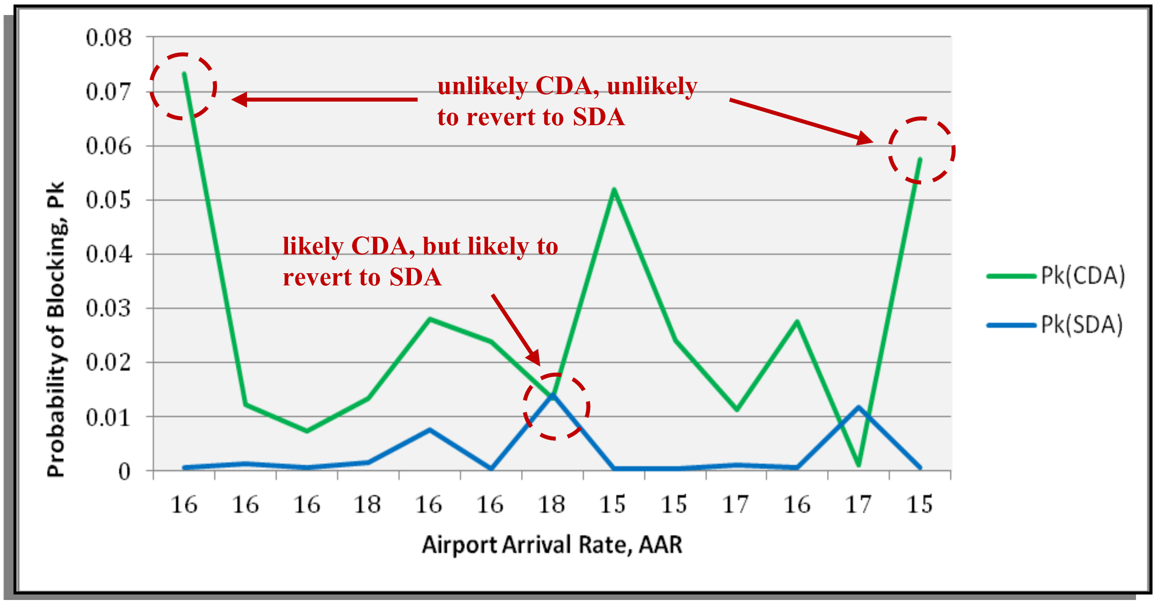

Figure 4.6 Application of CDA-A model using simulated data for $P_{k_{CDA}}$ and $P_{k_{SDA}}$.

Since the most critical factor that limits the widespread of CDA operations during high traffic periods is the need to further separate aircraft more than the standards separation minima, it is important to investigate the influence of this factor on $P_{k_{CDA}}$. As shown in Figure 4.7, there is a high similarity in the pattern of the two lines of $P_{k_{CDA}}$ and separation distance usually applied under CDA operations. That is, with high $P_{k_{CDA}}$, which means an aircraft may not conduct CDA at the considered *AAR*, the separation distance applied under CDA would be high, and the opposite is true, when $P_{k_{CDA}}$ is low, which means an aircraft may conduct CDA at the considered *AAR*, the separation distance would be low but with a likelihood to revert to SDA. This similar pattern that $P_{k_{CDA}}$ exhibits against the technical rule of separation distance under CDA operations ensures that our assumptions were consistent and verifies that our CDA-A model does not violate the actual standards of operations.

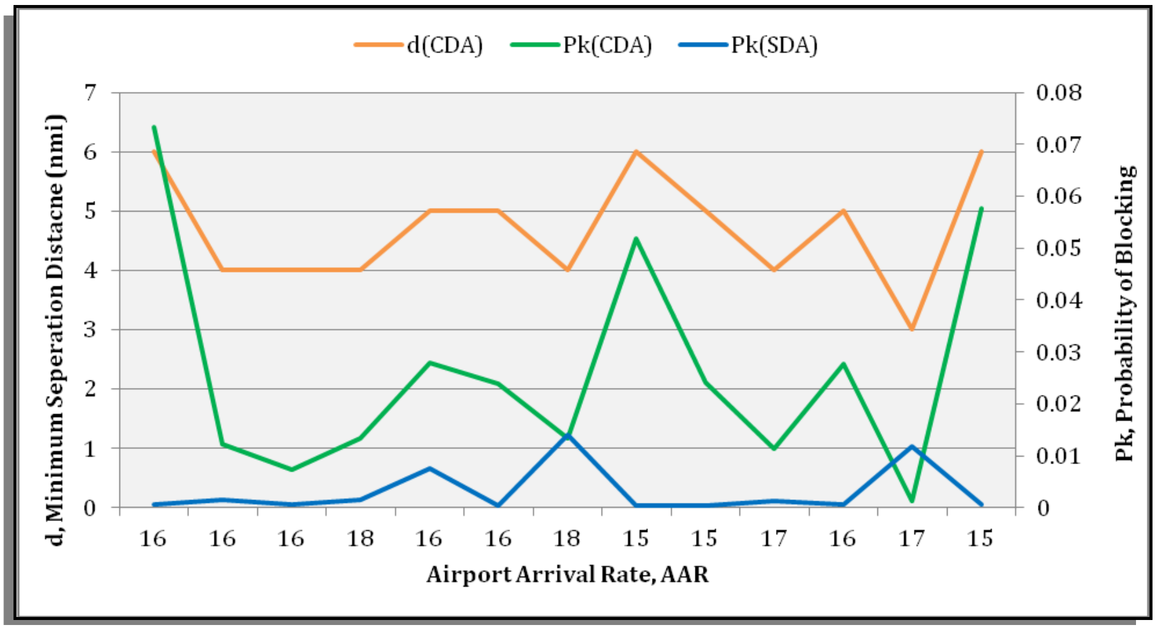

Figure 4.7 Impact of separation distance for CDA operations on $P_{k_{CDA}}$ and $P_{k_{SDA}}$.

4.5 Model Validation

To validate the our CDA-A model, actual flight data for flights operated to Nashville International Airport (BNA) will be used. These flight data have been extracted from off-line flight tracking logs, pre-processed, analyzed and systematically visualized in order to capture the descent profile of each flight to indicate whether it would be CDA or Non-CDA (i.e., SDA). As part of the validation process to our CDA-A model, an investigation to the relationship between some of the parameters used in building the model and the model output, P_k, is explored. Figure 4.8 illustrates the relationship between *k*, the number of aircraft that could be stacked in the stacking space, and P_k, as functions of the airport arrival rate, *AAR*. Values assigned to *AAR* on *x*-axis represents the actual fluctuation of demand at high levels of traffic over the busy period of operation at BNA airport; from 1200 to 1700 local time. The plot shows that as the airport arrival rate increases, the number of aircraft that could be stacked in the stacking space would decreases, and the probability of blocking increases. However, this is generally the case until a particularly high *AAR* reached, in this case 26 aircraft per hour. For instance, at an airport arrival rate of 23 aircraft per hour, the probability of blocking reaches a low value of 0.00961, corresponds to a high number of aircraft in the stacking space of 6 (rounded-down). This indicates that although the number of aircraft in stacking space could be high, still there is a low probability of blocking aircraft from embarking on CDA, despite high arrival rate. At airport arrival rate of 26 aircraft per hour, however, the probability of blocking line sharply reached a value of 0.07936, with the number of aircraft in stacking space less than 3, indicating a potential critically operational point that approximately no more than three aircraft may conduct CDA. Beyond this airport arrival rate, a decrease is observed in probability of blocking along with an increase in the number of aircraft in stacking space.

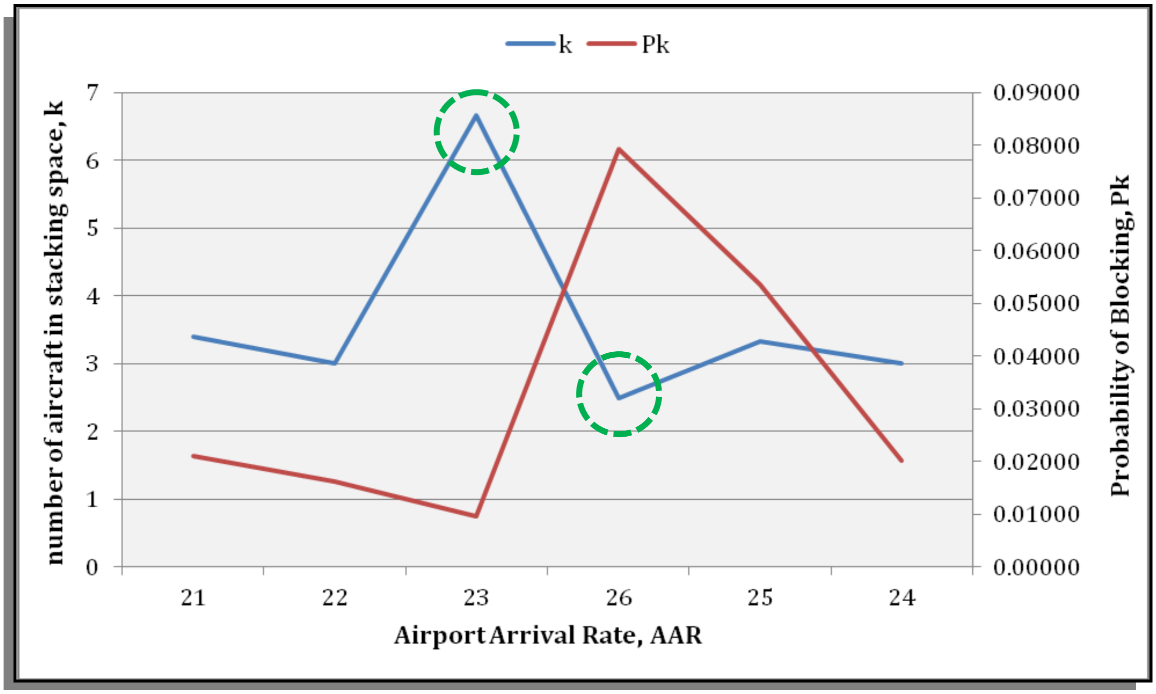

Figure 4.8 The relationship between number of aircraft in stacking space and P_k.

Comparing this implementation of CDA-A model with the actual flight data from BNA airport, it shows that at airport arrival rate of 26 aircraft per hour, no more than three consecutive CDA instances were observed, as shown in Table 5.2. In other words, the actual BNA data shows that ATC allowed CDA at this *AAR*, but it also shows that a limit of less than three, consecutive CDA instances was enforced, due to stacking space capacity, which in turn, dictate the number of aircraft that could—safely and efficiently—stacked and spaced. This validates our CDA-A model as we verified the behavior of number of aircraft in stacking space against the probability of blocking.

Table 4.2 Validation of CDA-A Model on BNA Flight Data for *AAR* of 26 Aircraft/Hr

hr	AAR	Aircraft	weight_class	Descent_Profile	Sp	d	k	RwyCap	mu	rho	Pk
15	26	H25B	Small	Non-CDA	17	4	4.25	43.25	11.4577	0.440678	0.008727
15	26	B737	Large	Non-CDA	19	3	6.333333	57.66667	11.4576	0.440678	0.001563
15	26	E135	Small	Non-CDA	19	4	4.75	43.5	11.8596	0.45614	0.006613
15	26	C56X	Small	Non-CDA	15	3	5	57.66667	11.8596	0.45614	0.005423
15	26	C56X	Small	CDA	16	3	5.333333	57	11.6552	0.448276	0.003848
15	26	B738	Large	CDA	17	3	5.666667	58	11.4576	0.440678	0.002704
15	26	CRJ7	Small	Non-CDA	19	4	4.75	43.75	11.8596	0.45614	0.006613
15	26	FA50	Small	Non-CDA	19	3	6.333333	58.33333	11.6552	0.448276	0.001719
15	26	C550	Small	CDA	15	3	5	57.66667	11.8596	0.45614	0.005423
15	26	B737	Large	CDA	18	3	6	57.66667	11.8596	0.45614	0.00246
15	26	E170	Large	Non-CDA	19	3	6.333333	58	11.6552	0.448276	0.001719
15	26	LJ45	Small	CDA	17	4	4.25	42.75	11.6552	0.448276	0.009268
15	26	MD80	Large	CDA	19	3	6.333333	58.33333	11.8596	0.45614	0.001892

Similarly, investigating the impact of minimum separation distance on the probability of blocking, as shown in Figure 4.9, shows that—as anticipated—an increase in separation distance will corresponds to an increase in the probability of blocking, especially at higher airport arrival rates (*AAR* of 26 aircraft per hour).

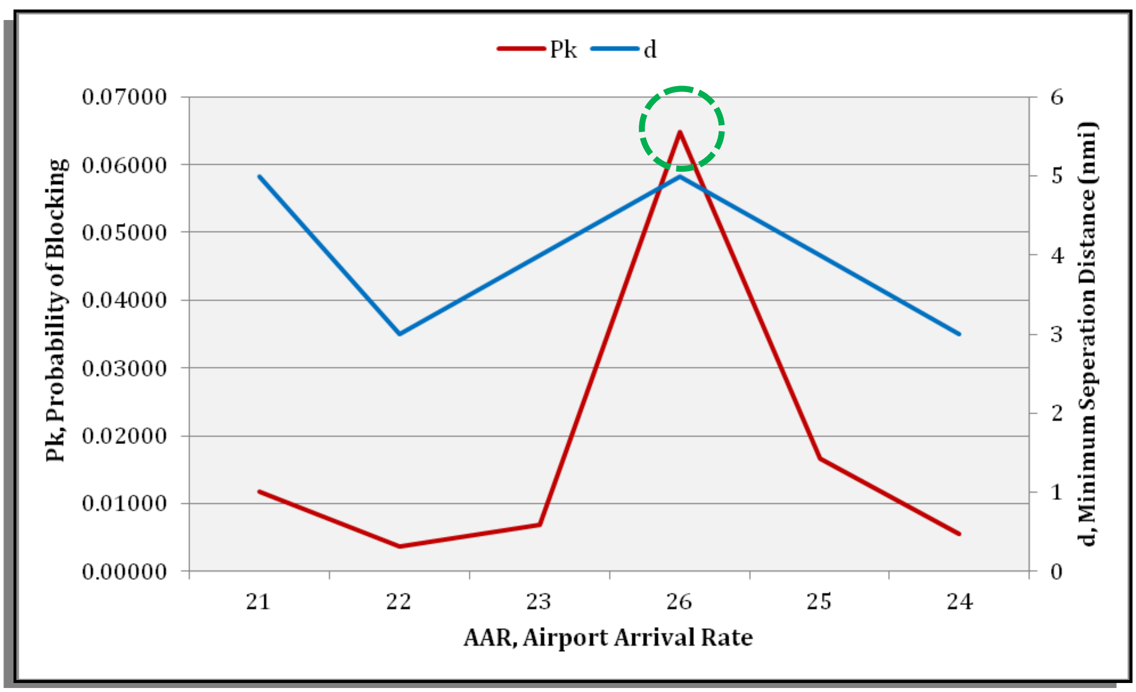

Figure 4.9 The relationship between minimum separation distance and P_k.

With respect to the size of the stacking space, S_p, Figure 4.10 below illustrates how this factor behaves when our CDA-A model applied to BNA actual flight data. The figure shows that as the airport arrival rate increases, the available space for stacking aircraft arrivals decreases, and in turn, the probability of blocking increases. P_k have reached its highest value, 0.0523, when S_p was at its lowest value, 15 nmi, and that was at *AAR* of 23 aircraft per hour. Then, P_k dropped to 0.0287 as S_p increased to 17 nmi, during an *AAR* of 26 aircraft per hour. This pattern is consistent with real ATM operations as the space available to stack aircraft arrivals at airports tends to vary in size as the rate of aircraft arrivals grow, which makes this space fills up quickly with stacked aircraft for landing. Hence, P_k as show, would play a vital role in deciding whether to conduct CDA or not, based on S_p, along with *AAR* and minimum separation distance.

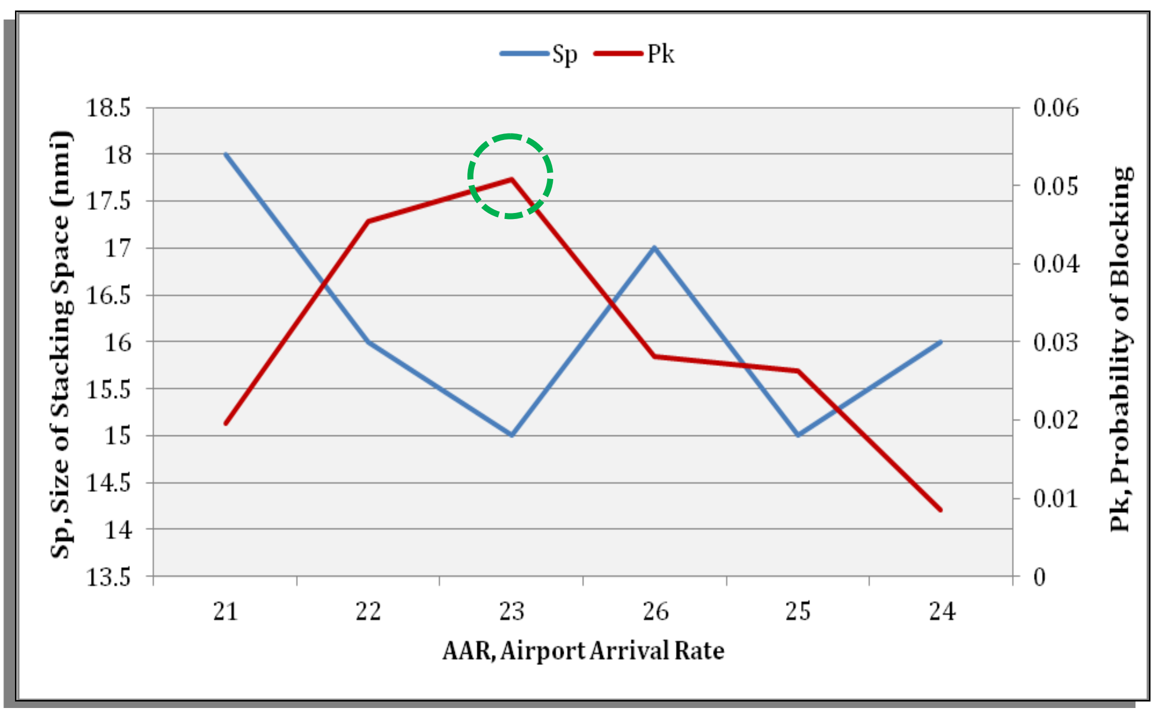

Figure 4.10 The relationship between stacking space size and P_k.

To further validate our CDA-A model, $P_{k_{CDA}}$ and $P_{k_{SDA}}$ has been calculated using the actual flight data of BNA. As shown in Figure 4.11 below, critical operational points occur at *AAR* of 24 and 25 aircraft per hour, respectively. As previously mentioned in the CDA-A application section, the lines of $P_{k_{CDA}}$ and $P_{k_{SDA}}$ intersects at operationally critical point at which it is likely to conduct CDA yet likely to revert to SDA, given the *AAR*.

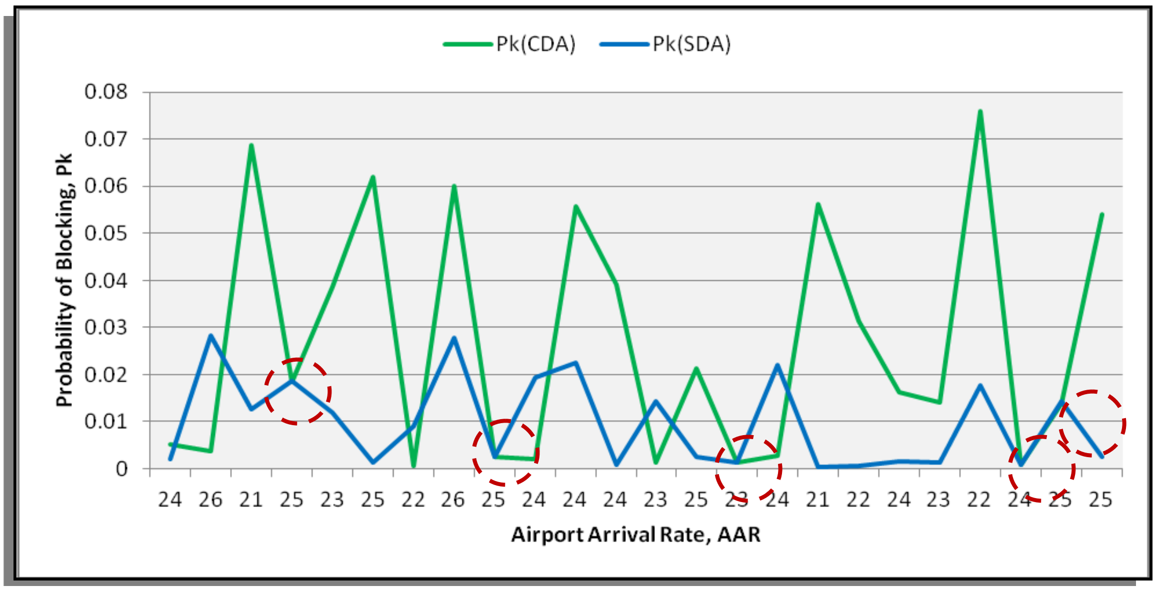

Figure 4.11 Validation of CDA-A model using flight data of BNA for $P_{k_{CDA}}$ and $P_{k_{SDA}}$.

Comparing this results with the actual data of BNA airport, shown in Table 4.3, it shows that almost all of the descent profiles, except for two, were Non-CDA at *AAR* of 25 aircraft per hour. Perhaps some of these aircraft may initiate their descent with CDA, but since the safe management of ATM operations is the responsibility of ATC assuming full authority over the airspace they manage, it is at the ATC's discretion to revert to from CDA to SDA to safety purposes.

Table 4.3 BNA Flight Data at *AAR* of 25 and 26 Aircraft Per Hour

hr	AAR	Aircraft	weight_class	Descent_Profile
16	25	C550	Small	Non-CDA
16	25	B737	Large	Non-CDA
16	25	C680	Small	Non-CDA
16	25	A319	Large	Non-CDA
16	25	E170	Large	Non-CDA
16	25	C501	Small	Non-CDA
16	25	B738	Large	CDA
16	25	BE40	Small	Non-CDA
16	25	E145	Small	Non-CDA
16	25	H25B	Small	Non-CDA
16	25	E55P	Small	Non-CDA
16	25	E55P	Small	Non-CDA
16	25	C56X	Small	Non-CDA
16	25	B737	Large	Non-CDA
16	25	CRJ	Small	Non-CDA
16	25	B737	Large	Non-CDA
16	25	C501	Small	Non-CDA
16	25	MD88	Large	Non-CDA
16	25	CL30	Small	Non-CDA
16	25	CL60	Small	CDA
16	25	C56X	Small	Non-CDA
16	25	F900	Small	Non-CDA
16	25	B733	Large	Non-CDA
17	24	CRJ7	Small	CDA
17	24	B737	Large	CDA
17	24	LJ25	Small	Non-CDA
17	24	LJ45	Small	Non-CDA
17	24	B733	Large	Non-CDA
17	24	B738	Large	CDA
17	24	B738	Large	Non-CDA
17	24	C650	Small	CDA
17	24	E135	Small	Non-CDA
17	24	GALX	Small	CDA
17	24	E170	Large	Non-CDA
17	24	A320	Large	Non-CDA
17	24	E170	Large	CDA
17	24	B738	Large	Non-CDA

Finally, as P_k help determine the threshold beyond which CDA is unsafe to be adopted during an airport arrival rate, it provide an effective metric to estimate the arrival rate of CDA operations, λ_{CDA}. This estimation could be carried out through a typical counting process, either manual or automated (e.g., FAA's Tower Operations Count) for CDA instances that has been successfully adopted once CDA-A model is applied and P_k calculated. Once λ_{CDA} is estimated, and the AAR is known, then the Continuous Descent Approach Adoptability Factor (CDA-AF) could be calculated, using equation (3.1) previously presented in Chapter 3. Figure 4.12 shows the calculations results of CDA-AF using BNA actual flight data. For example, at local time 1500, *AAR* was 26 aircraft per hour, and the number of CDA instances—based on CDA-A validation process—was 13 instances, which provide an estimate for λ_{CDA}. Then the CDA-AF was calculated as 0.5, meaning CDA-A was 50%, and P_k, on average, is 0.02435.

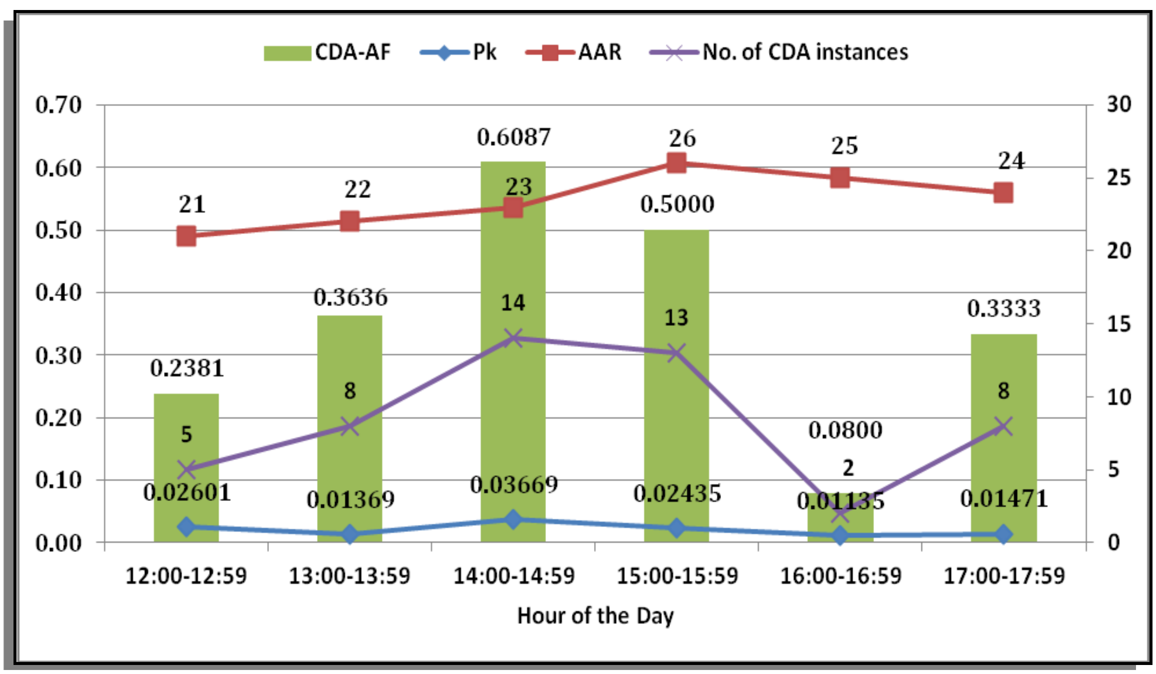

Figure 4.12 Calculating CDA Adoptability Factor (CDA-AF) and P_k using BNA data.

CHAPTER 5

CDA PREDICTABILITY MODEL

This chapter presents the second component in this work, which uses predictive analytics to assist controllers manage adopting more CDA operations during periods of high demand through prediction. The objective of this chapter is to present a framework that can be used to develop CDA predictive models to accurately predict CDA instances during high traffic at airports. This framework is based on data-driven systems approach.

5.1 Framework and Data

5.1.1 Data-driven System Approach Framework

The framework used in this work to develop CDA predictive models basically integrates two approaches, namely; data-driven system approach, and data engineering approach, whereas the first refers to the systematic approach of viewing and modeling critical elements of the system under study as data-generating components (Jian-Xin and Zhong-Sheng, 2009), and data engineering refers to broad methods and techniques generally draws from fields related to data science such as data mining, machine learning, and predictive modeling. The framework that encompasses the phases of this method is illustrated in Figure 5.1.

The framework (Alharbi and Abdel-Malek, 2016) consists of two modules; Descent Profile Analytics, and CDA Predictive Analytics, and starts with acquiring off-line flight tracks logs that contains tracking information and data generated from ADS-B

(Automatic Dependant Surveillance-Broadcast) systems for each flight arrived at a given airport. Typically, each flight tracking history has been recorded in one log, however, the file that has the raw data contains all the logs of all the flights arrived between 1200 and 1700 local time at that airport. Thus, preparing and preprocessing this unsorted, raw data to identify, label, and then extract flights with CDA descent profile is the next phase.

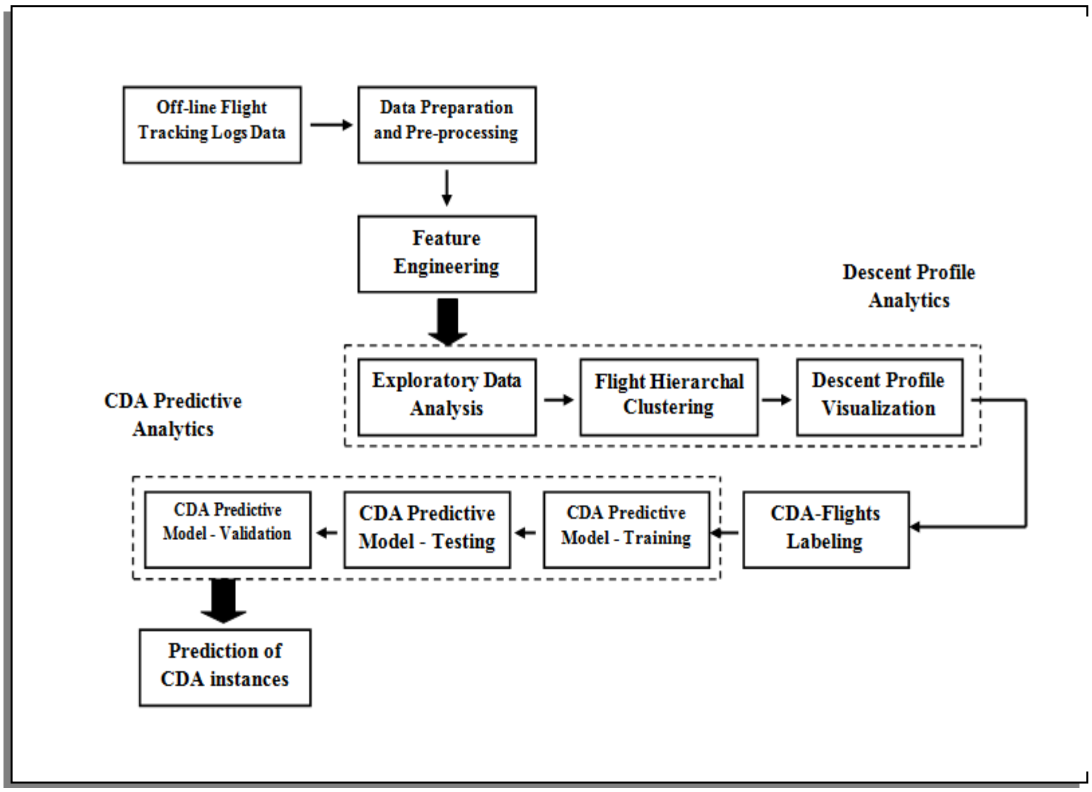

Figure 5.1 Data-driven system approach framework to predict Continuous Descent Approach (CDA) instances at airports.

Although the off-line flight tracking logs are rich in navigational information, such as latitude, longitude, and time; and aircraft performance information, such as altitude and rate of descent, however, in order to capture flights with CDA descent profiles from this data, we need to construct new features that help us to do so through *Feature Engineering*. Requiring domain-specific knowledge with the data, feature engineering generally refers to the process and techniques used for generating new features from raw data that better represent and facilitate the underlying problem for predictive modeling (Brownlee, 2014). In this section, feature engineering was used to create new variables or features from existing ones, such as altitude defined with reference to the top of descent (TOD) point at which aircraft initiates descent, time aircraft takes to descent, and along-track distance during descent. Since perhaps the best to way to identify a flight's descent profile as a CDA is by plotting the descent profile, feature engineering is highly important to visualize the entire descent profile of each flight we have in the data in order identify, label, and distinguish flights with CDA profiles from other flights with non-CDA descent profile. In order to group flights in the data based on some common characteristics, Hierarchal Clustering Analysis (HCA) was used to cluster flights into similar groups using the Levenshtein distance formula. By clustering flights into similar groups based on similar attributes, we were able to compute the along-track distance using the haversine distance formula that calculates the great-circle between two points for each flight entry in the data. Plotting this distance against the altitude, the descent profile for each flight entry was clearly visualized for CDA-flights labeling.

5.1.2 Data Used and Datasets Created

As stated earlier, the data used for analysis comprised of two components; traffic and weather data. The traffic data represents flights arrivals to a major US airport; Nashville International Airport (BNA) on June 17th, 2015, between the hours of 1200 and 1700 local time. This data has been provided by flight tracking information provider (i.e., *FlightAware.com*) that provides on-line tracking services to flights from and to airports via the FAA's ASDI (Aircraft Situation Display to Industry) and using Automatic Dependent Surveillance - Broadcast (ADS-B) stations. Typically, ADS-B relies on satellite communication for navigation and aircraft performance information sharing in the national airspace system (NAS), and it is a critical technology for the FAA's Next Generation Air Transportation (NextGen) program. The traffic data on the aforementioned day represents the busiest day in terms of traffic during the year of 2015. Since the information in the off-line flight tracking logs were specifically reported from ADS-B stations, then the data that can be extracted from this logs considered spatio-temporal and thus would accurately approximates the 4D (latitude, longitude, altitude, and time) of aircraft's position over flight trajectory. Generally, and for each flight, the traffic data includes features such as origin-destination airports, aircraft type, latitude, longitude, course, direction, aircraft speed, and rate of descent. Features in the traffic data are shown in Table 5.1 below.

Table 5.1 Features in the Traffic Data from the Off-line Flight Tracking Logs

#	Feature Name	Type	Description
1	Flight ID	Categorical	Unique identifier for flights in the data
2	Time in UTC	Numerical	Time in Universal Time
3	Aircraft	Categorical	Aircraft type (e. g., B737)
4	Origin	Categorical	Name of origin airport
5	Destination	Categorical	Name of destination airport
6	En-route	Numerical	Time flight's took en route between origin-destination airports
7	Aircraft Speed	Numerical	Aircraft's indicated airspeed measured in knots (KIAS)
8	Ground Speed	Numerical	Aircraft's speed relative to ground measured in knots
9	Altitude	Numerical	Altitude, in feet, at which aircraft's position is reported
10	Rate of Descent	Numerical	Aircraft's rate of descent in ft/min.

On the other hand, the weather data are obtained from the Meteorological Aviation Reports (METAR) generated from the METAR stations. Typically, weather data includes information such as wind speed, wind direction, cloud type, cloud height, temperature, and visibility. Features in the weather data are shown in Table 5.2 below.

Table 5.2 Features in the Weather Data from the Off-line Flight Tracking Logs

#	Feature Name	Type	Description
1	Flight_Rule	Categorical	Flights' rule applied at destination airport based on meteorological flight conditions (e. g., VFR)
2	Wind_Dir.	Numerical	Direction of wind based on magnetic directions (e. g., 270 means wind blows from the west)
3	Wind_Speed	Numerical	Speed of wind in knots
4	Cloud_Type	Categorical	Type of formation clouds is taking at the destination airport (e. g., BKN = Broken)
5	Cloud_Height	Numerical	Distance, above ground level, between cloud base and cloud top at the destination airport (e.g., 25,000 ft)
6	Visibility	Numerical	Distance, in statute mile, at which a runway at the destination airport can be clearly discerned (e. g., 10 sm)
7	Temp	Numerical	Temperature, measured in Fahrenheit, at the destination airport
8	Dew_Point	Numerical	Temperature, measured in Fahrenheit, at which dew forms at the destination airport
9	Rel_Humidity	Numerical	The amount of water vapor present at air expressed as a percentage of the amount of the amount needed for saturation at the same temperature (e. g., 51%)
10	Pressure	Numerical	The atmospheric pressure, measured in inches Mercury, at the destination airport (e. g., 30.1 in. Hg)

5.2 Data Preparation and Preprocessing

In this section, examples of issues we have encountered while preparing for the off-line flight tracking data for analysis are presented. Resolving these issues include extracting and creating the dataset from the off-line flight tracking logs, transform variables (e.g., landing time from continuous to discrete) and treating missing within the dataset, and finally ensure the quality of the dataset before loading it into our predictive model.

5.2.1 Missing Values Treatment

As an example of the challenges faced when preparing the off-line flight tracking data for modeling, a flight instance that has disconnection of ADS-B reporting of an aircraft's position. This often resulted in several missing values in latitude and longitude in the tracking log of a flight instance, which accordingly causes missing values in rate of descent values as well. This partial missing of values has required manual intervention to fix the output of our descent profile analytics module. In other similar but extreme case, a flight instance that has complete missing of its performance data from the tracking log, such as ground speed, altitude, and rate of descent. Generally, we assume that the missing values in the data are missing systematically, not randomly, though, due to potential error in data reporting. Fortunately, less than 3 instances with such complete missing of flight tracking log data was found, which supports our assumption that this missing of data is randomly occurring in the data due to, say, an unexpected fault in the ADS-B transceiver that receives the information from the aircraft and transmit it to a reporting system.

In addition, we came across flight instances in the off-line tracking data logs that could not be captured by our descent analytics module due to some sort of cut in the tracking log itself. For example, a flight instance tracking log shows constant altitude over changing time latitudes and longitudes coordinates, which indicates a cruise phase of flight. However, after a decrease in altitude corresponds by negative change in the rate of descent, which indicates the initiation of descent phase, the tracking reporting suddenly terminates. We spotted this issue in two flight instances in BNA dataset. To explain this issue based on our understanding of the data and air traffic operations in terminal maneuvering area (TMA) around airports, it is likely that such flight instance was a fly-over flight. As our descent profile analytics module would not be able to capture such flight instance for analysis, nor we were able to fix it due to the large missing portion of the tracking log itself, we chose to exclude such flight instances from the dataset by list-wise deletion.

5.2.2 Duplicated Flight Instances

Another example of issues we had in preparing the off-line flight tracking data is the repetition of a flight instance with the same unique Flight ID entry but with different time reporting. This repetition causes our profile analytics module to duplicate plotting the two flight instances in one plot, and thus, the visual representation of the descent profile was distorted. Due to the close gap in time between two flights instances in this situation, it is likely that such instance has been a touch-and-go landing. This issue was resolved by separating the two same-Flight ID flight instances into two entries with the two different times that have been reported.

5.3 Feature Engineering

Broadly speaking, Feature Engineering (FE) refers to the process of using domain knowledge on transforming extracted information from raw data into features that better represent the underlying problem to predictive modeling, and ultimately, resulting in improved accuracy on unseen data. FE was used in this work to create new features from BNA dataset after preparing and processing the off-line flight tracking logs raw data.

In order to make our dataset ready for predictive modeling, the first feature we needed to create is related to the different aircraft types appears in BNA airport data. In practice, air traffic controllers (ATC) separate aircraft primarily based on weight categories that has been established on maximum certified take-off weight. For example, the term "heavy" is used by ATC to determine separation minimums, speeds, descent rates, and other aircraft characteristics. Therefore, we grouped all aircraft types in BNA airport data into three broad weight classes using criteria based on maximum take-off weight (MTOW), as shown in Table 5.3.

Table 5.3 Aircraft Types in BNA Airport Data Grouped by MTOW

Aircraft Weight Class	Small	Large	Heavy
MTOW Criteria	MTOW < 88,184 lb (*e. g., C750, CRJ2, GLF4*)	300,000 lb > MTOW > 88,184 lb (*e. g., B739, A321, E170*)	MTOW > 300,000 lb (*e. g., A388*)

Likewise, the off-line flight tracking data shows no indication of the descent profile type. For our analysis, we need to distinguish flights with CDA profile among other flights that are Non-CDA profile. In order to achieve this, and as it will be detailed as follows. We used great-circle distance computation for aircraft positions along flight trajectory to create two new features; top of descent (TOD) altitude and TOD distance. The TOD altitude refers to the altitude at which the TOD point has been identified using descent profile visualization, and the TOD distance refers to the along-track distance of the TOD with respect to touchdown point on runway. Although the entire descent profile has been plotted and visualized, the TOD altitude and TOD distance features has been extracted for each flight entry for CDA analysis.

As the times for tracking and actual arrival of flights were appeared in the data in the form of *hh:mm:ss* (i.e., 13:45:32), we had to decompose these times into a more manageable, numerical feature that will be easier to used for predictive modeling. This led to creating a feature called Hour of the Day, that represents a numerical value of the hour segment of the actual arrival time of flights, while also keeping the minute segment of the original time variable for reference only. The reason to do this is that due the availability of more than one active runway at the airport, often there is a chance that some flight entries have the same hour and minute of arrival/landing time as they have been arriving/landing at the same time but on different runways.

5.4 Descent Profile Analytics Module

5.4.1 Exploratory Data Analysis

In this section, a basic summary statistics of the variables distribution in BNA dataset. As we have divided the BNA dataset into training, validation, and testing datasets in order to build our predictive model, it is important to note that this exploratory analysis has been conducted only on the training dataset, which accounts of 70% of BNA dataset. Table 5.4

lists the features we created from BNA dataset and used to build a CDA predictive model.

Generally, BNA training dataset contains 78 observations of flight instances, and 9 variables as follows: hour of day, airport arrival rate (*AAR*), aircraft weight class, top of descent (TOD) altitude, TOD distance, wind direction, wind speed, descent time, and finally the target variable we aim to predict; descent profile, that indicates whether the descent profile of each flight was a CDA or not. All variables are numerical, except weight class and descent profile, both are categorical. For aircraft weight class, BNA training dataset contains 48 observations of Large, 66 observations of Small, and no observations for Heavy.

Table 5.4 Features Created for CDA Instances Prediction

#	Feature Name	Description
1	Hour_of_Day	Hour when the flight landed on runway
2	AAR	Airport Arrival Rate
3	Aircraft_Class	Aircraft turbulence weight class
4	TOD_Alt	Altitude of the Top of Descent (TOD) point
5	Wind_Speed	Wind speed
6	Wind_Dir	Wind direction
7	Descent_Time	Elapsed time an aircraft takes to descent
8	TOD_dist	Along-track distance of TOD point from runway
9	Descent_Profile	Aircraft's descent profile (CDA or Non-CDA)

The TOD altitude, which represent the altitude at which have initiated descent from the TOD point, measured in feet (ft), shows lowest value of 5,900 ft, highest value of 43,000, and mean of 30,892 ft, and most of CDA instances where concentrated between 26,500 ft and 43,000 ft. Similarly, the TOD distance, which represents the along track distance of the TOD point, measured in nautical miles (nmi), has lowest value of 10 nmi, highest value of 250 nmi, mean of 136.1 nmi, variance of 3,026 nmi, and 25th and 75th quartiles of 98 nmi and 173.7 nmi, respectively; and all the CDA instances were concentrated between 75 nmi and 160 nmi. Additionally, BNA dataset has more Non-CDA instances comparing to CDA instances over the time frame considered. BNA dataset reveals correlation relationship between the features we have created from BNA data. For example, there is a correlation of factor 0.886 between the time aircraft takes to descent from TOD point to touchdown point on runway (i.e., *Descent_Time*) and the along-track distance of TOD point (i.e., *TOD_dist*).

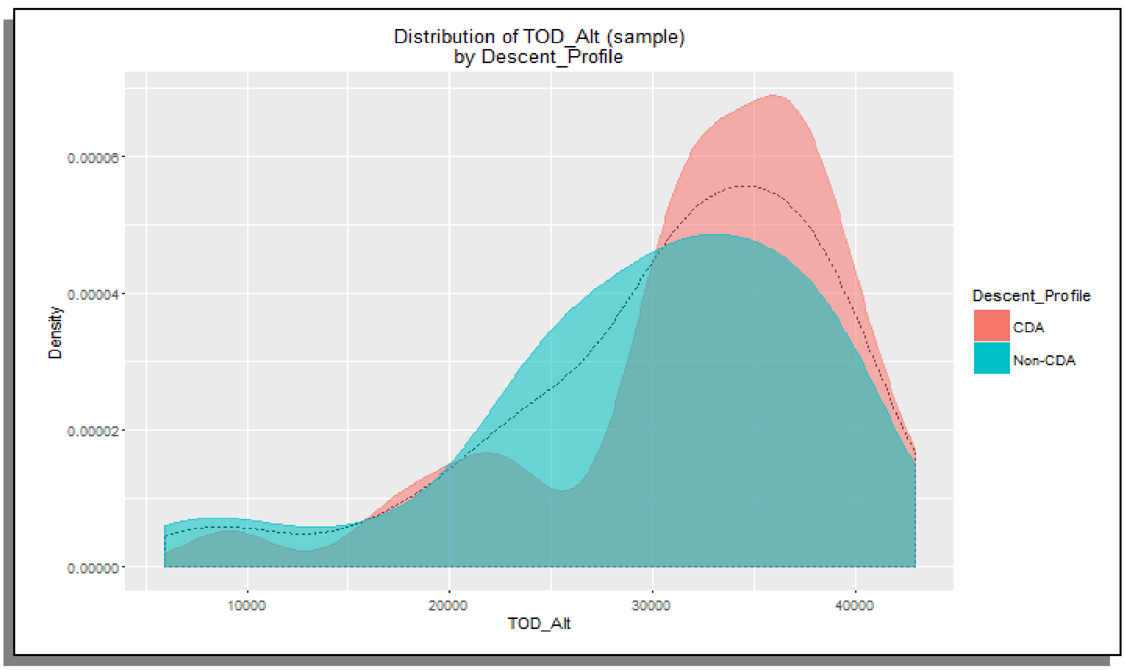

Figure 5.2 Density distribution of Top of Descent (TOD) altitude grouped by Descent Profile from BNA dataset.

Another correlation with factor of 0.632 between *Descent_Time* and the altitude at which TOD point has been located (i.e., *TOD_Alt*). Also, a correlation of 0.806 between the along-track distance of TOD point and the altitude at which TOD point has been located. These high correlations are due to the fact that *Descent_Time* has been confounded from *TOD_Alt* and *TOD_dist* variables, which all has been created from BNA dataset to extract knowledge about CDA instances. Figure 5.4 illustrates these and other statistical characteristics revealed from BNA training dataset.

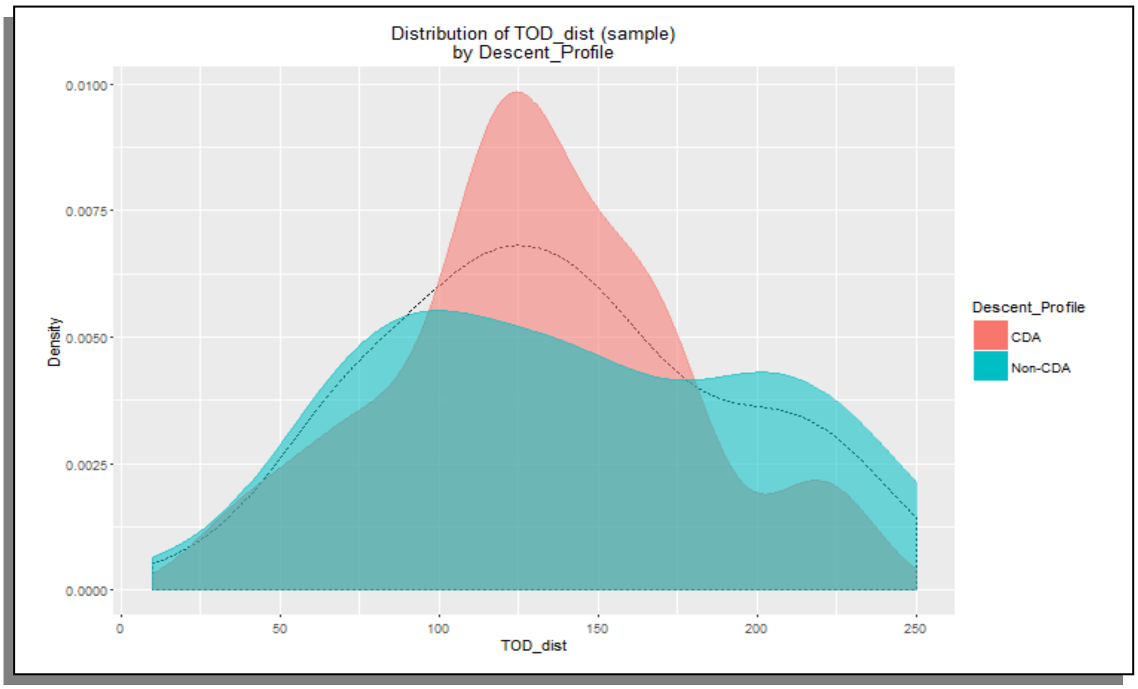

Figure 5.3 Density distribution of Top of Descent (TOD) point distance from touchdown point grouped by Descent Profile from BNA dataset.

5.4.2 Hierarchical Clustering of Flights

The off-line flight tracking logs contains data of different flights arrivals to BNA airport as a collection of numerous data entry instances corresponds to a single flight. In order to build a structure of clusters from this data, hierarchal clustering analysis (HCA), also referred to as hierarchal clustering, which is a widely-used clustering method when there are more than two variables in the dataset was used. In essence, hierarchal clustering only use similarities of instances or observations in the data with aim to find groups such that instances in a group are more similar to each other than instances in different groups (Alpaydin, 2010).

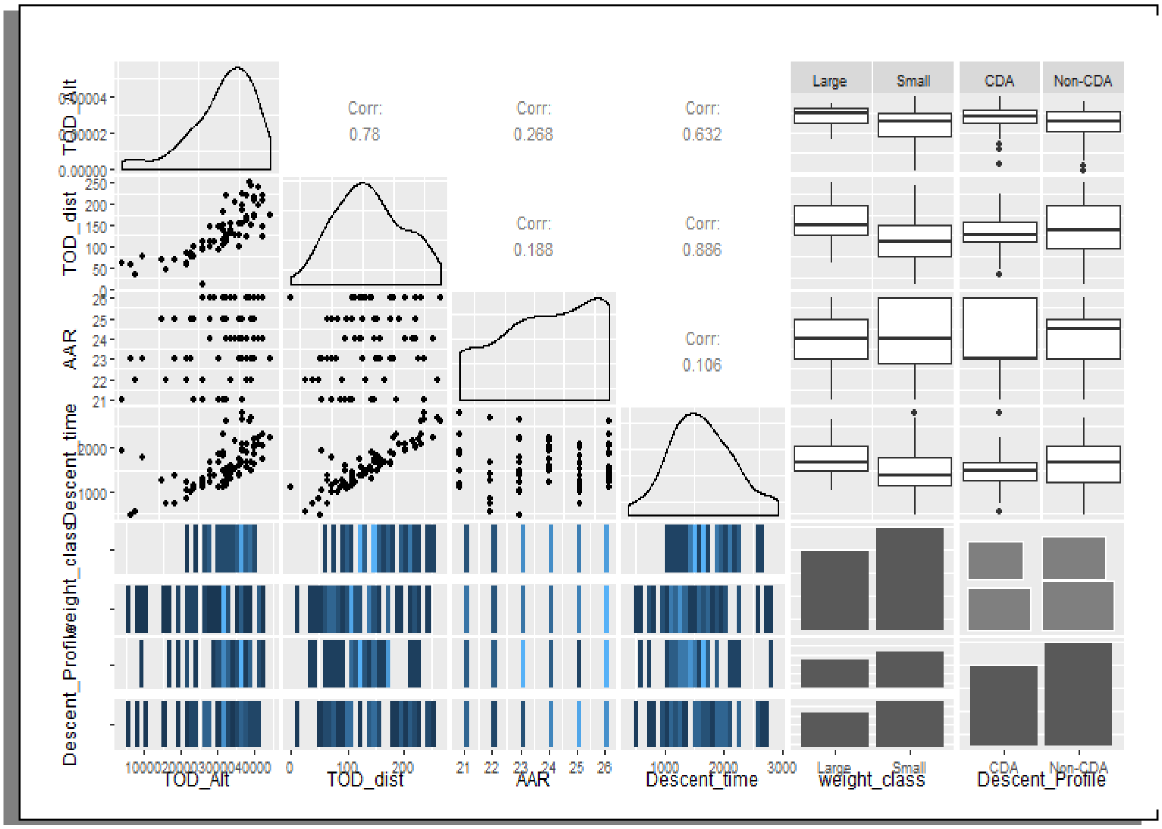

Figure 5.4 Statistical characteristics of features in BNA airport training dataset.

Among hierarchal clustering methods, we particularly used the agglomerative hierarchal clustering that is based on measures of distance between two pairs of clusters to determine which pair is the best for merging into clustering group. This hierarchal clustering method also provides a convenient graphical display in which the entire sequence of merging of clusters could be displayed in a tree-like representation called *dendrogram* (Hand et al., 2001). BNA data was clustered using HCA by grouping different flight data entry instances to a Flight ID; a unique identifier for each flight in the off-line flight tracking logs data.

Suppose F_i where $i = 1, \ldots, n$ be the Flight ID entries for the different positions of a flight in the flight data, then the attributes for every flight entry are defined in Table 5.5 and the dendrogram for hierarchical clustering of flight data is illustrated in Figure 5.5.

Table 5.5 Different Attributes of Flight Data Entry Instances

#	Attribute Symbol	Attribute Description
1	*la*	Latitude of the flight
2	*lo*	Longitude of the flight
3	*d*	Haversine distance between the current position of the flight to the position of the airport
4	*a*	Altitude of the flight
5	*g*	Ground Speed of the flight
6	*t*	Recorded time stamp of the flight
7	*w*	Flight weight class categorized as: Small, Large, and Heavy
8	*f*	Flight data entry instance
9	*F*	Flight ID corresponding to a flight in the data

The latitude and longitude of every flight data entry instance is converted to a distance value with respect to the position of the airport. In particular, the haversine distance formula calculates the distance between the current position of the flight and the position of the airport. The haversine formula provides the great-circle distance between two points—that is, the shortest distance over the earth's spheroid surface— from their latitudes and longitudes. It is a special case of spherical geometry which is based on the law of haversines which relates to the sides and angles of spherical triangle

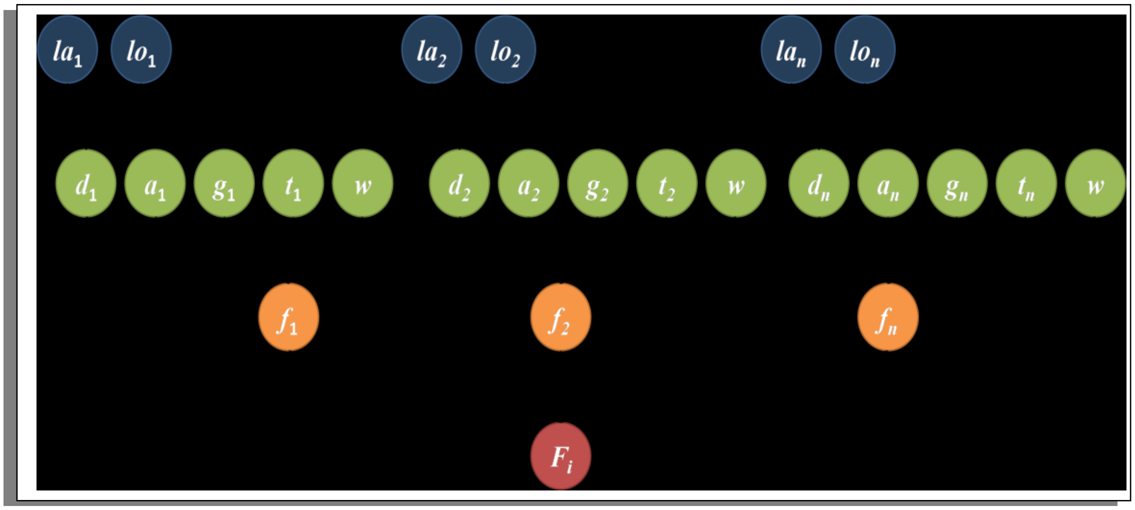

Figure 5.5 Dendrogram of the Hierarchal Clustering Analysis of Off-line Flight Tracking Data

For any two points on a sphere, the haversine distance is given by:

$$d = 2r \arcsin\left(\sqrt{\sin^2\left(\frac{\phi_2 - \phi_1}{2}\right) + \cos(\phi_1)\cos(\phi_2)\sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right) \tag{5.1}$$

where d is the distance between the two points, r is the radius of earth (r ≈ 6371 kilometers ≈ 3440.064 nautical miles), Φ_1, Φ_2, are the latitude of point 1 and point 2, respectively; and λ_1, λ_2, are the longitude of point 1 and point 2, respectively. To compute the distance between two sequences of clusters, we used the Levenshtein distance that usually used to measure the distance between two strings. The Levenshtein distance formula was specifically used due to the fact that Flight ID in the off-line flight tracking data could be viewed as a string of characters (e.g., RAX698-1434547022-68-0).

For two strings a and b of lengths $|a|$ and $|b|$, respectively, then the Levenshtein distance between a and b is giving by $\mathrm{lev}_{a,b}(|a|,|b|)$ as follows:

$$\operatorname{lev}_{a,b}(i,j) = \begin{cases} \max(i,j) & \text{if } \min(i,j) = 0, \\ \min \begin{cases} \operatorname{lev}_{a,b}(i-1,j) + 1 \\ \operatorname{lev}_{a,b}(i,j-1) + 1 \\ \operatorname{lev}_{a,b}(i-1,j-1) + 1_{(a_i \neq b_j)} \end{cases} & \text{otherwise.} \end{cases} \quad (5.2)$$

Accordingly, all the flight data instances with the same Levenshtein distance are grouped into a cluster. Therefore, if the flight data has *m* flights, then *m* different clusters are formed using hierarchical clustering with Levenshtein distance. The flight data entry instances, *f*, are compared with each other and the distance is calculated so as to group similar instances. Based on the distance, the flight data entry instances corresponding to a flight are grouped together so as to form a flight cluster, F, which represents all the data entry instances of a flight through the unique identifier Flight ID.

After clustering the data into clusters for each flight, we further group the data according to the weight class of the flight. The flight weight class is subdivided into three categories namely, Small, Large and Heavy. The final clustering for each airport contains three clusters corresponding to the weight class with flight clusters belonging to different weight class. Each flight cluster contains different flight data entry instances for the different positions of the flight in the flight descent trajectory.

5.4.3 Descent Profile Visualization

After clustering analysis of the flight entries has been completed, and the great-circle distance computed for each flight entry, then clustered flight entries are now ready to be visualized to determine the profile descent of each flight entry in BNA datasets. That is, the descent profile graph that plot the altitude of aircraft as a function of the distance to touchdown will be created for each flight entry in the dataset. By doing so, we will be able to distinguish between flights with CDA and flights Non-CDA descent profile for CDA instances analysis. The CDA instances analysis could be flights-focus or time-focus. For flight-focus examples, the descent profile for two flight entries from BNA dataset is illustrated in Figure 5.6 and Figure 5.7, respectively. Figure 5.6 shows the descent profile, as been generated from our Descent Profile Analytics module, of a Falcon 20— a small business jet and thus belongs to the Small weight class we have grouped from the data—with a clear Non-CDA profile as it shows a step-down descent that entirely differs from CDA profile. Similarly, Figure 5.7 shows a descent profile but for another small aircraft, Hawker 400, that exhibits a smooth, CDA profile from cruise altitude of 23,000 ft to touchdown. For time-focus CDA instances analysis, Figure 5.8 shows the count of descent profiles at BNA grouped by aircraft weight classes, the hour of the day for the time block expressed by the data, and the label of the descent profile (i.e., CDA or Non-CDA).

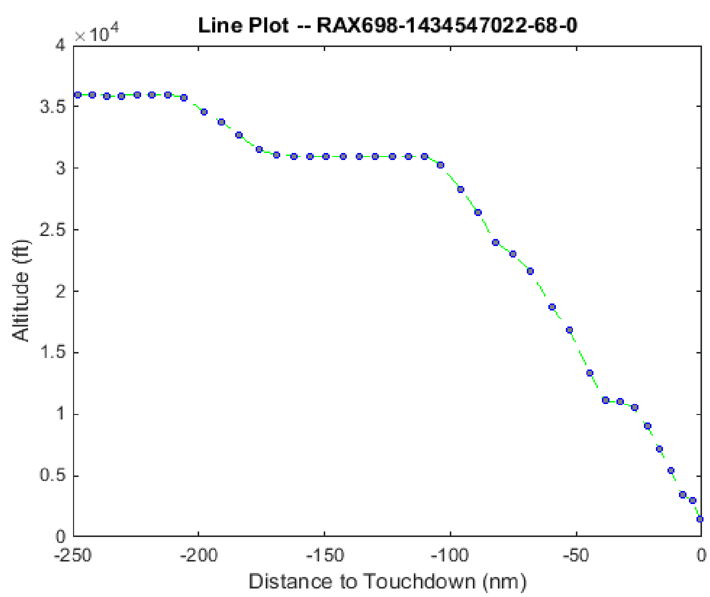

Figure 5.6 Descent Profile of Falcon 20 Aircraft (small business jet) at BNA Shows a Typical step-down Descent Arrival.

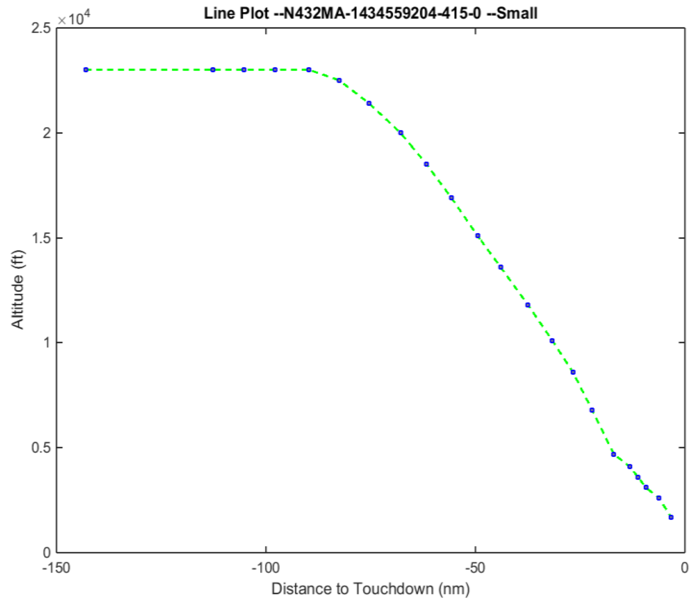

Figure 5.7 Descent Profile of Hawker 400 Aircraft (small business jet) at BNA Shows a Typical CDA.

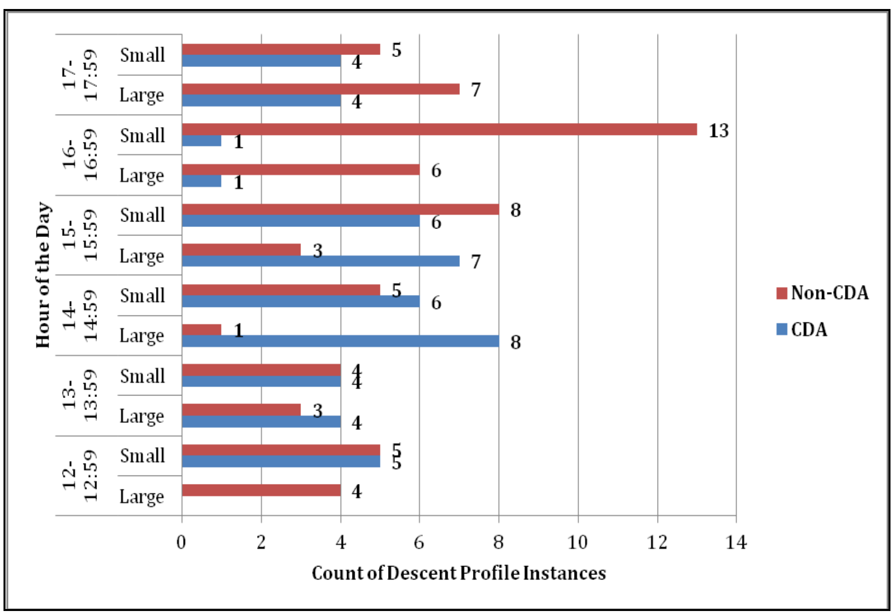

Figure 5.8 Summary of Descent Profile Instances at BNA Shows Level of CDA Adoptability Analyzed based on Hour of the Day and Aircraft Weight Class.

5.5 CDA Predictive Analytics Module

Two distinct statistical classifiers used to build a CDA predictive model. The first classifier is an ensemble classification model that combines multiple decision trees into a single model with boosting method to improve the prediction accuracy of CDA instances, while the second classifier is Support Vector Machines (SVM) that extends the support vector classifier to non-linear boundary between binary classes by enlarging the feature space.

5.5.1 Decision Trees with AdaBoost

An ensemble of classification and regression trees (CART) was used to build a CDA predictive model. The main strategy of CART is to partition a sample of data using binary rules to split parent nodes so the child nodes are more homogeneous than the parent node. CART models can be built for classification or regression problems and have the ability to handle very high-dimensional datasets. Additionally, CART have advantages of such as easy interpretability through graphical representation and ability to handle qualitative variable without the need to create dummy variables. The major disadvantage of CART models is in the accuracy level that may be lower than other classification methods (James et al., 2014).

In this section, a CART classification model was built using decision trees to predict instances of CDA descent profile at BNA airport. To overcome the accuracy issue with CART decision trees and improve the performance of CDA predictive model, the Boosting approach was used. First presented in (Freund and Schapire, 1997) and extended to the concept of combining models together as an ensemble to reduce misclassification error, bias, and variance in (Freund and Schapire, 1999), the Boosting algorithm is an efficient approach to predictive models building. We use a popular variant of the Boosting algorithm called *AdaBoost* (Freund and Schapire, 1999), abbreviated from *Adaptive Boosting*, to aggregate many decision trees sequentially and so each tree is grown using information from previously grown trees.

5.5.2 Support Vector Machines

First presented in (Vapnik and Vapnik, 1998), the approach taken by Support Vector Machines (SVM) method is to identify planes (in the case of multiple dimensions represented by many input variables in the prediction problem) that separates observations with different values of the target variable. Finding such hyperplanes would enable us to search for the plane that maximizes the area between the binary classification groups, which are in our case, CDA and Non-CDA profile. As the observations in BNA dataset are not linearly separable, fortunately the idea of creating new variables from the original input variables in the data (i.e., via feature engineering) will enhance variables separation through kernel function created by the SVM algorithm. A SVM with Gaussian Basis kernel function was used to build a CDA predictive model.

5.5.3 Training, Validating, and Testing of CDA Predictive Model

To build our CDA predictive model, we partition BNA dataset into three, independent subsets; 70% for training, 15% for validation, and 15% for testing. This partitioning is done randomly to ensure each subset is representative to the whole collection of observations in BNA dataset. We build—and train— our CDA predictive model using the training dataset. To evaluate the performance of our CDA predictive model but on previously unseen dataset, the validation dataset, also known as the design dataset, is used as it provides early estimate on the predictive model performance, and depending on the performance, a chance to tune the parameters used to build the model (e. g., number of trees, minimum splits...etc.). Finally, the performance of our CDA model would be further evaluated on the third partition of BNA dataset; the testing dataset, also known as the *hold-out* or *out-of-sample* dataset, that is, it contains randomly selected observations from the full BNA dataset that are not used in any way in building the CDA predictive model and not in-common with neither the training nor validation datasets, to ensure that the model will perform well on new observations (Williams, 2011).

When training and validating the CDA predictive model we built using the decision trees with AdaBoost, the following parameters has been defined; the number of trees to build, the maximum depth of any node of the final tree (i.e., *maximum depth*), and minimum number of observations that must exist in BNA dataset at any node in order for a split of that node to be attempted (i.e., *minimum splits*). We also "*stumped*" our CDA model during training by allowing the decision trees to comprise a single node (i.e., maximum depth equals 1) resulting in a single split in the training dataset. In testing our CDA model on the testing dataset, though, we set the previously mentioned parameters as follows: 350 trees to be built, maximum depth of 30 for any node, and minimum number of observations of 10 at any node to split. After several trials with different values of these parameters between training and validation experiments, we found that using "*stumps*" our CDA model performance improve in terms of reduction of error rate, and it became ready for testing. Similarly, when training and validating the CDA predictive model built using SVM, we experimented using different types of kernel functions, including Gaussian Basis, linear, and polynomial functions, to provide a nonlinear separation to observations. We found that the Gaussian Basis kernel function performs well with our CDA model. With the SVM, the parameters we had to set was the *cost* or penalty parameter (*C*), which has been set to 1. For training our CDA model using the SVM algorithm, the output will provide an estimate to a parameter (*Sigma*) for the radial basis kernel function, and the error calculated from the training

5.5.4 Performance Evaluation of Predictive Methods Used

In this section, we evaluate the performance of our CDA predictive model that we built using decision trees with AdaBoost and SVM methods. The error matrix, also known as *confusion matrix*, is an appropriate model performance evaluation tool, especially when predicting a categorical target, as it is the case with our CDA predictive model. Essentially, the error matrix displays the predicted results from a predictive model versus the actual values from the dataset used for building and testing that model. Two error matrices are presented from the testing dataset for each CDA predictive method we have used; AdaBoost and SVM, that shows the actual counts.

Table 5.6 illustrates the performance of our CDA predictive built using decision trees with AdaBoost based on actual counts versus predicted. Error rate, or misclassification rate, of (1+0)/19 = 5.26%. That is, our CDA predictive using decision trees with AdaBoost has a correct classification rate, or accuracy rate of (6+12)/19 = 94.74%, which is a high accuracy rate. Similarly, Table 6.7 illustrates the performance of our CDA predictive built using SVM with error rate of (2+0)/19 = 10.52%. That is, the accuracy rate of our CDA predictive model with SVM equals (5+12)/19 = 89.47%. In terms of error and accuracy rates, AdaBoost outperforms the SVM for our CDA predictive model. In terms of *Precision* (i.e., *the fraction of instances the classifier precisely predicted*), the AdaBoost has a precision of 6/(6+0)=1, and the SVM has the same precision since 5/(5+0)=1. In terms of *Sensitivity*, also called *true positive rate*, which refers to the fraction of the descent profile instances detected by the classifier as CDA. The AdaBoost has a sensitivity of 6/(6+1)=85.7%, while the SVM was 5/(5+2)=71.4% sensitive to predictions of descent profile classes. Finally, in terms of *Specificity*, also called true negative rate, which refers to the fraction of descent profile instances identified as Non-CDA. The AdaBoost has specificity of 12/(12+0)=1, and the SVM has the same specificity since 12/(12+0)=1 (Zumel and Mount, 2014). Considering these performance measures, the AdaBoost may be more suitable than SVM for building a CDA predictive model to predict CDA instances at airports.

Table 5.6 Error Matrix for CDA Predictive Model using AdaBoost

Counts	Predicted		
Actual	*CDA*	*Non-CDA*	*Total*
CDA	6	1	7
Non-CDA	0	12	12
Total	6	13	19

Table 5.7 Error Matrix for CDA Predictive Model using SVM

Counts	Predicted		
Actual	*CDA*	*Non-CDA*	*Total*
CDA	5	2	7
Non-CDA	0	12	12
Total	5	14	19

Finally, Table 5.8 summarize the performance evaluation of both AdaBoost and SVM classification methods.

Table 5.8 Summary of Performance Evaluation of Classification Methods Used

Performance Measure	**Classification Method Used**	
	AdaBoost	**SVM**
Error Rate	5.26%	10.52%
Accuracy Rate	94.74%	89.47%
Precision (*the fraction of instances the classifier precisely predicted*)	1	1
Sensitivity (*true positive rate*)	85.7%	71.4%
Specificity (*true negative rate*)	1	1

CHAPTER 6

CONCLUSION AND FUTURE RESEARCH

Continuous Descent Approach (CDA), the flight technique by which aircraft descend continuously from cruise altitude to final approach fix (FAF) and to land on runway with idle or near-idle engine setting. CDA allows aircraft to remain at higher altitudes longer, and minimize or eliminate level flight segments. The idle thrust settings result in reduced fuel burn, less noise over large portions of the flight path, reduced environmentally harmful emissions, and saving in flight time. Unlike the traditional descent and approach, in which aircraft are typically directed by air traffic controllers (ATC) to fly a step-down vertical profile with extended level flight segments and speed constraints for spacing. Because of these level segments require thrust utilization to maintain altitude, the result is increased flight time, noise exposure, and emissions levels. Thus, CDA is a cornerstone in international and national civil aviation modernization programs that aims to efficient aviation operations with less environmentally damaging footprints.

Due to its uninterrupted operational trait such that once the idle descent is commenced, it is hardly possible to react on ATC instructions during CDA, making it critical to safety as minimum allowable longitudinal separation distance may likely be violated. In addition, ATC needs to accurately predict the new position of aircraft conducting CDA along its flight path, and with potential violation in separation distance, ATC would typically follow a more conservative approach to manage the traffic. Therefore, ATC often impose larger separation distance than the standards, which may significantly impact airport capacity and throughput. For this reason, CDA implementation has been limited to light to moderate traffic, and a large stacking space on developing methods. In spite of the large research efforts conducted in this area, little attention has been given to develop metrics that help ATC estimate threshold in which CDA would be safe to implement for certain traffic levels. This dissertation focused on contributing to fill this gap by developing analytical and predictive models that can be used to capture that measure.

In this dissertation, models are developed that aim at addressing the accommodation of more CDA operations during higher traffic levels than currently acceptable. The models introduced are divided into two main components; CDA Adoptability (CDA-A), and CDA Predictability (CDA-P). By definition, CDA-A refers to the level of CDA operations an airport can safely and efficiently accommodate and accept per hour. Mathematically, CDA-A is expressed by the CDA Adoptability Factor (CDA-AF), which is the ratio of average arrival hourly rate of CDA operations at an airport, λ_{CDA}, to total aircraft arrival hourly rate at that airport (i.e., Airport Arrival Rate "*AAR*"). On the other hand, CDA-P refers to the ability of predicting CDA operations, with high accuracy, based on specific operational and weather features during high traffic levels, which will provide improved tactical management and enhanced adoptability to CDA operations under future but similar traffic and weather conditions.

Analyzing airspace structure around airport offers a systematic way of developing an analytical model that adequately captures the elements associated with descent and approach procedures. As it was shown in Chapter 3 of this dissertation, detailed description to descent and approach procedures, in the light of the two, commonly used descent profiles; CDA and Step-down Descent Approach (SDA). Furthermore, detailed comparison between CDA and SDA was presented to reveal the technical differences between these descent profiles from an operational stand point. This paved the way to introduce the concept of CDA-A, and its metric, CDA-AF, and to further investigate the factors that plays a critical role in affecting CDA-A, which include, but not limited to, AAR, arrival mix and separation requirements, wind speed and direction, airspace constraints, and traffic at neighboring airports. As a building block to CDA-A model, time aircraft take to land under CDA and SDA was estimated using two distinct methods; descent rules of thumb, and Base of Aircraft Data's (BADA) Aircraft Performance Model (APM). The two methods were described in detail and compared in terms of level of complexity, aircraft weight requirement, and consideration of wind effect. While a computational algorithm was developed to facilitate and carry out the calculations of aircraft's estimated landing time using descent rules of thumb, the calculations using BADA APM were carried out using BADA's online calculation tool; Aircraft Performance Calculation (APC). Finally, the results from the two methods were evaluated against actual landing times for various aircraft landed on Nashville International Airport (BNA). It is found that our computational algorithm provides an acceptable error rate for a strategic guidance to ATC.

Building on the preliminaries presented in Chapter 3, and based on our comprehensive analysis for the parameters that governs CDA implementation during high traffic levels, such as terminal maneuvering area (TMA) and size of stacking space to stack aircraft arrivals, the CDA-A model was introduced and detailed to define and capture a threshold beyond which CDA becomes unsafe to adopt. Based on this analysis, two probabilities were captured and presented, the first probability defines CDA threshold, while the second probability represents the upper bound of the system. In the CDA-A model, these parameters can be captured in a single measure, which we distinguish as the Probability of Blocking, which is defined as the fraction of time an aircraft's request to embark on CDA is denied principally due to safety and because the stacking space within the TMA is busy and congested. Essentially, the significance of this measure is to help answer a pressing question that ATC face during high traffic periods: *How many CDA operations the airport can safely and efficiently accommodate and up to what traffic intensity?* The CDA-A model and its output, the Probability of Blocking, help answer the question to provide better tactical decision making through efficient management to adopt more CDA operations during high traffic levels.

Currently, we found that the CDA-A model can be used to capture the threshold beyond which CDA would be unsafe to adopt, CDA-A was applied through a numerical example using simulated data. A scenario was developed to represent a traffic at mid-sized international airport during an afternoon busy level of demand, typically between 1200 and 1700 local time. A number of parameters used in the development process of CDA-A model and have direct influence on CDA adoptability were identified, such AAR, size of stacking space, and aircraft approach speed, with typical ranges for these parameters were defined based design standards and previous pattern from historical data. The CDA-A application results revealed that when the probability of blocking for CDA and SDA calculated and fitted, a high probability of blocking for CDA indicates that it is unlikely to adopt CDA at the corresponding AAR, yet it is unlikely to revert to SDA, as it is so unlikely to start descending with CDA at the first place. Furthermore, CDA-A application results revealed critical operational points at which the probability of blocking for CDA and SDA intersects when plotted against AAR. These critical points capture the challenge that ATC faces at high traffic levels when attempt to adopt more CDA operations. At these critical points, the probability of blocking for CDA is low, indicating that it is likely to adopt CDA at a corresponding high AAR. However, with the intersection with the probability of blocking for SDA, it also indicates that it is likely to revert to SDA. As such, the probability of blocking has identified and captured the threshold beyond which CDA adoption would be unsafe at these critical points.

To validate the CDA-A model, actual data of flights operated to Nashville International Airport (BNA) was used. These flight data have been extracted from off-line flight tracking logs, pre-processed, analyzed, and systematically visualized in order to capture the descent profile of each flight to indicate whether it would be CDA or Non-CDA (i.e., SDA). The validation approach was set to test that the results obtained from the CDA-A model application using simulated data would match the expected behavior. A sensitivity analysis to the parameters considered in developing the CDA-A model by running the simulation multiple times and varying the parameters over range of high and low values. When applying the CDA-A model using the actual flight data from BNA airport, it has shown that at airport arrival of 26 aircraft per hour, no more than three consecutive CDA instances were observed. When investigating the impact of minimum separation distance on the probability of blocking, flight data from BNA airport shows that—as anticipated—an increase in separation distance will corresponds to an increase in the probability of blocking, especially at higher airport arrival rates. Furthermore, when CDA-A model was applied on BNA actual flight data, it was found that as the probability of blocking help determines the threshold beyond which CDA is unsafe to be adopted during an airport arrival rate, it provide an effective metric to estimate the arrival rate of CDA operations. This estimation could be carried out through a typical counting process for CDA instances that has been successfully adopted once CDA-A model is applied and the probability of blocking calculated. As such, the arrival rate of CDA operations was estimated, and CDA-AF, along with the probability of blocking using BNA flight data were calculated. As an example, it was shown that the CDA-A model capture CDA threshold at local time 1500, when *AAR* was 26 aircraft per hour, and the number of CDA instances—based on CDA-A validation process—was 13 instances, which provide an estimate for arrival rate of CDA operations, CDA-AF was calculated as 0.5, meaning CDA-A was 50%, with the probability of blocking, on average, is 0.02435.

For the CDA-P, an indirect data-driven CDA model was developed essentially based on data-driven system approach and aim at extraction of traffic features, such as aircraft type and speed, altitude, and rate of descent; and weather features, such as wind speed and direction, from off-line flight tracking logs. The framework consists of two modules Descent Profile Analytics, and CDA Predictive Analytics, with objective to develop CDA predictive models that predicts CDA instances during high traffic periods at airports. The data used for analysis comprised of two components; traffic and weather data. The traffic data represents flights arrivals to a major US airport; Nashville International Airport (BNA) on June 17th, 2015, between the hours of 1200 and 1700 local time. data has been provided by flight tracking information provider (i.e., *FlightAware.com*) that provides on-line tracking services to flights from and to airports via the FAA's ASDI (Aircraft Situation Display to Industry) and using Automatic

Dependent Surveillance - Broadcast (ADS-B) stations. Since the information in the off-line flight tracking logs were specifically reported from ADS-B stations, then the data that can be extracted from this logs considered to be spatio-temporal data and thus would accurately approximates the 4D (latitude, longitude, altitude, and time) of aircraft's position over flight trajectory. On the other hand, the weather data are obtained from the Meteorological Aviation Reports (METAR) generated from the METAR stations.

As an example of the challenges faced when preparing the off-line flight tracking data for modeling, missing values treatment was carried out to deal with missing data, such as disconnection of ADS-B reporting of an aircraft's position and repetition of a flight instance with the same unique Flight ID entry but with different time reporting. Furthermore, Feature Engineering (FE), the process of using domain knowledge on transforming extracted information from raw data into features that better represent the underlying problem to predictive modeling, and ultimately, resulting in improved accuracy on unseen data. FE was used in this work to create new features from BNA dataset after preparing and processing the off-line flight tracking logs raw data. Features created using FE include examples such as aircraft weight classes (e.g., Heavy, Large, and Small) and Top of Descent (TOD) altitude and distance. For TOD features extraction, great-circle distance computations for aircraft positions along flight trajectory were used to create these two new features.

As part of the Descent Profile Analytics Module, exploratory data analysis was conducted to statistically summarize BNA airport dataset, which we divided into training, validation, and testing datasets in order to build our predictive model. It is important to note that this exploratory analysis has been conducted only on the training dataset, which accounts of 70% of BNA dataset. The off-line flight tracking logs contains data of different flights arrivals to BNA airport as a collection of numerous data entry instances corresponds to a single flight. Hierarchal Clustering Analysis (HCA), also referred to as hierarchal clustering, was used in order to build a structure of clusters from this data. The latitude and longitude of every flight data entry instance is converted to a distance value with respect to the position of the airport, and the haversine formula was used to calculate the great-circle distance between two points—that is, the shortest distance over the earth's spheroid surface— from their latitudes and longitudes. As clusters were created, we used the Levenshtein distance that often used to measure the distance between two strings. The Levenshtein distance formula was specifically used due to the fact that Flight ID in the off-line flight tracking data could be viewed as a string of characters.

After clustering analysis of the flight entries has been completed, and the great-circle distance computed for each flight entry, then clustered flight entries are now ready to be visualized to determine the profile descent of each flight entry in BNA datasets. That is, the descent profile graph that plot the altitude of aircraft as a function of the distance to touchdown was created for each flight entry in the dataset. By doing so, we were being able to distinguish between flights with CDA and flights Non-CDA descent profile for CDA instances analysis. In addition, the CDA instances analysis could be flights-focus or time-focus.

Working on the CDA Predictive Analytics Module, two distinct statistical classifiers used to build CDA predictive models. The first classifier is an ensemble classification model that combines multiple decision trees into a single model with boosting method to improve the prediction accuracy of CDA instances, which decision trees with Adaptive Boosting (AdaBoost), while the second classifier is Support Vector Machines (SVM) that extends the support vector classifier to non-linear boundary between binary classes by enlarging the feature space.

To build our CDA predictive model, BNA dataset was partitioned into three, independent subsets; 70% for training, 15% for validation, and 15% for testing. This partitioning was done randomly to ensure each subset is representative to the whole collection of observations in BNA dataset. We have built—and trained— our CDA predictive model using the training dataset. To evaluate the performance of the CDA predictive model but on previously unseen dataset, the validation dataset, also known as the design dataset, is used as it provides early estimate on the predictive model performance. Finally, the performance of the CDA predictive model was further evaluated on the third partition of BNA dataset; the testing dataset, also known as the *hold-out* or *out-of-sample* dataset, as it contains randomly selected observations from the full BNA dataset that are not used in any way in building the CDA predictive model and not in-common with neither the training nor validation datasets, to ensure that the model will perform well on new observations. The error matrix, also known as *confusion matrix*, is an appropriate model performance evaluation tool, especially when predicting a categorical target, as it is the case with our CDA predictive model was used to evaluate the performance of our CDA predictive model that we built using decision trees with AdaBoost and SVM methods. At the end of the evaluation process, it was found that the CDA predictive model built using decision trees with AdaBoost has an error rate of 5.26%, which means the accuracy rate is 94.74%, and sensitivity of 85.7%. On the other hand, the CDA predictive model built using SVM has an error rate of 10.52%, which means the accuracy rate is 89.47%, and sensitivity of 71.4%. In general, comparing the performance of the two models, we found that the AdaBoost outperform the SVM in terms of accuracy and sensitivity.

The research conducted in the production of this dissertation have reached the following contributions:

i. Introduced the concept of Continuous Descent Approach Adoptability (CDA-A) as the level of CDA operations an airport can safely and efficiently accommodate and accept per hour to air transportation industry and air traffic management (ATM) sector. Developed and presented Continuous Descent Approach Adoptability Factor (CDA-AF), a metric through which CDA-A can be measured and expressed.

ii. Developed, tested, and validated an analytical model for CDA-A that capture CDA and Step-down Descent Approach (SDA) operations, based on factors that impact CDA implementation, such as airport arrival rate, separation distance between aircraft, and runway capacity, to help estimate the threshold beyond which CDA adoption is unsafe. Developed and defined the Probability of Blocking, P_k, a metric that help estimate the maximum traffic level beyond which CDA adoption would be unsafe.

iii. Developed a framework, based on data-driven system approach, that help predict—with high accuracy—CDA instances at airports during high traffic periods for CDA-P.

iv. Utilizing the developed framework, a CDA predictive model was built, validated, and tested using two distinct predictive modeling methods; Decision Tress with Adaptive Boosting (i.e., AdaBoost), and Support Vector Machines (SVM). This confirms that predicting CDA operations during high traffic periods is achievable and highlights the need to adopt the presented framework as a building block for trajectory prediction module in the core of an automated decision support system (DSS) that help ATC make sound judgment on CDA operations as they monitor the progress of each aircraft.

The results of this research opened the doors to multiple, new investigations, and paved the way for possible future research topics, including:

i. Expand the application of the CDA-A model to larger airports with higher level of demands, but are not at their maximum capacity yet.

ii. Investigate more factors that have influence on CDA adoptability, such traffic at neighboring airports, and include them in the CDA-A model for more comprehensiveness and enhanced representation.

iii. Apply the CDA-A model to Point Merge System (PMS) to investigate the feasibility of the model under different airspace structure.

iv. Enhance the CDA predictive model by sampling data for more days from various seasons of the year, to capture variation in weather and traffic conditions, for the same busy time frame considered in order to obtain more number of flights observations at a particular airport.

v. Utilize the framework presented for CDA Predictability model to develop an airport-specific data-driven model by considering attributes such as certain arrival procedures and runways used for landing to predict CDA instances and improve CDA-A. To be used as a building block for an automated prediction decision support system (DSS), this model could be built to be direct (i.e., in the on-line mode) through appropriate connection with the operational infrastructure in-use to provide real-time prediction based on real-time feed of data inputs.

APPENDIX A

ALGORITHM TO COMPUTE AIRCRAFT LANDING TIME

Figure A.1 shows the pseudo code for the developed computational algorithm to estimate aircraft landing time based on descent rules of thumbs. The algorithm initializes by reading data that contains flight information for flights operated at a given airport. These flights should be processed and sorted to identify descent profile (e.g., CDA or Non-CDA) of each flight. Then the algorithm reads altitudes, ground speed, approach speed, and number of descent requirements that an aircraft has to follow based on air traffic controller (ATC) instructions. Regardless of whether the descent profile is CDA or Non-CDA, ATC instructs pilots to descend on stages of altitude reductions over which pilots has to report their set of information to ATC, such as current altitude, speed, and rate of descent, at the end of each stage. The output of the algorithm is compute total time for aircraft to descend over all these stages.

To run the algorithm, the altitude that the aircraft needs to dissipate, and the distance associated with that altitude difference needs to be defined. Then, based on the number of descent requirements stages, the algorithm iterates between current altitude and new altitude that the aircraft will reach, computing altitude difference, rate of descent, and how far the top of descent (TOD) point is located from the new altitude. Since the speed that should be reported to ATC below 10,000 feet is ground speed rather than true airspeed, the algorithm will consider this operational standard while computing total descent time and distance to descent.

Algorithm 1: Computing Landing Time for Aircraft

Data: A: Altitudes Set
GS: Ground Speed
AS: Approach Speed
N: Number of descent requirements
Result: TD: Total time of descent

{Altitude needs to be dissipated};
{Distance for descent};
DD=0;
{Time for descent};
TD=0.0;
for $(n = 1; n < N; n++)$ **do**
    {Current Altitude};
    CA=A_{n-1};
    {New Altitude};
    NA=A_n;
    Δh_n= CA - NA;
    {TOD point location};
    TOD = $\frac{\Delta h_n}{300}$;
    {Rate of Descent (ROD)};
    ROD= $GS \times 5$;
    if $CA \leq 10000$ **then**
        DD =DD + [(CA-NA)$(AS)^{-1}$];
        TD= TD + $\frac{DD}{AS} \times 60$;
    else
        DD =DD+ $[\Delta h_n \times (GS)^{-1}]$;
        TD= TD + $\frac{DD}{GS} \times 60$;
    end
end
Return TD;

Figure A.1 Pseudo code of the developed computational algorithm to calculate landing time for different aircraft types with Continuous Descent Approach (CDA) and Step-down Descent Approach (SDA).

APPENDIX B

BASE OF AIRCRAFT DATA (BADA) AIRCRAFT PEFORMANCE CALCULATION (APC) TOOL

Figure A.1 shows the Graphical User Interface (GUI) of Base of Aircraft Data's (BADA) Aircraft Performance Calculation (APC) tool. As one of BADA's Support Tools, APC provides access to online implementation of the BADA Aircraft Performance Model (APM), which include database of various performance parameters for several types of aircraft, and APM's formulas that developed by EUROCONTROL. When using APC, the user would have the option to run an APC session for a single aircraft or multiple aircraft. In addition, APC provides other basic calculations for aircraft speed conversions, and atmosphere model.

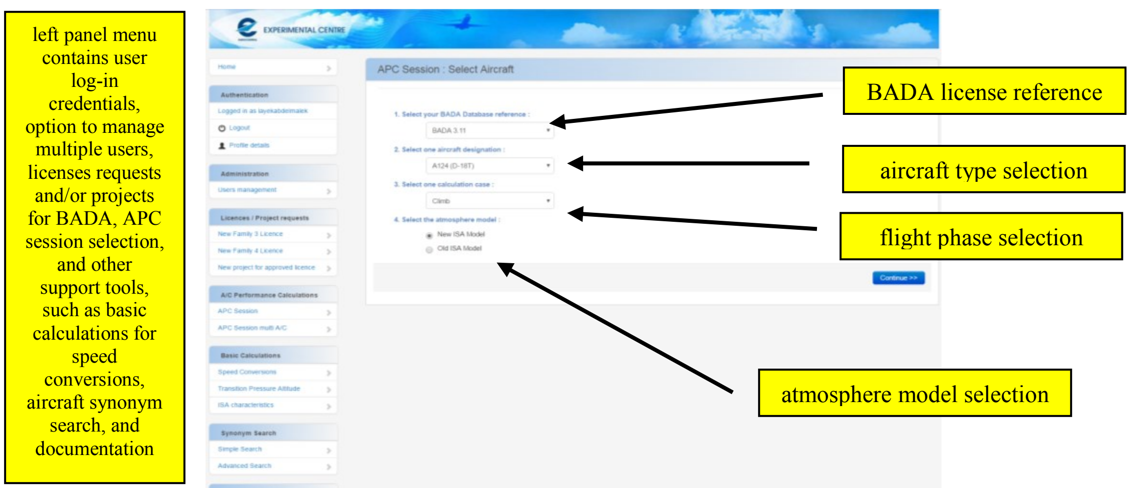

Figure B.1 BADA APC Graphical User Interface (GUI) for a single aircraft session. The main area lists the license that was issued to the user by EUROCONTROL, a drop-down list from which the user can select the aircraft type to calculate the performance parameters, another drop-down list that prompts the user to select a flight phase for performance calculations (e.g., climb, cruise, descent), and selection for whether to run the calculations based on the old or new International Standard Atmosphere model.

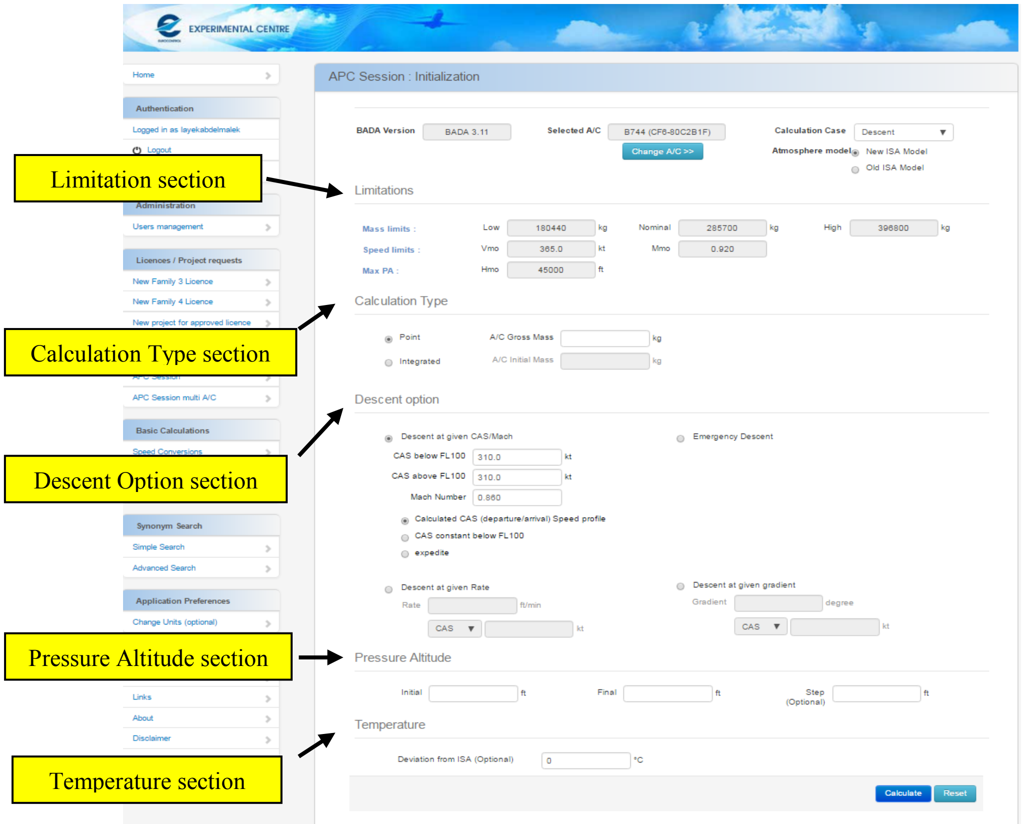

Figure B.2 APC initialization for a single aircraft session. After summarizing the selections of BADA license, aircraft type, flight phase (Descent) and ISA model, the main area lists five main sections; Limitations, Calculation Type, Descent Option, Pressure Altitude, and Temperature.

Figure B.2 shows the initialization of a single aircraft APC session. For this sample session, Boeing 747-400 with engine CF6-80C2B1F was selected, the flight phase to calculate performance parameters was *descent*, and the new ISA model was selected in this session. The main area is divided into five sections; **Limitations**, **Calculation Type**, **Descent Option**, **Pressure Altitude**, and **Temperature**, respectively. In limitations, limits have been set for aircraft mass, speed, and pressure altitude. The user has the option to select nominal values, or set values that must not exceed these limits. The calculation type section gives the user the option to select whether this calculation could be done with reference to point, so a value for gross weight for the selected aircraft has to entered, or integrated calculations over the descent profile, so the user has to enter an initial mass for the selected aircraft to start the calculations. Descent option gives the user to select between three options; descent at given calibrated airspeed (CAS)/Mach, descent at given rate, or descent at given gradient. Pressure altitude section prompts the user to enter initial and final values for altitude, with option to define a step at which altitude is decreasing. Finally, the temperature section prompts the user to optionally enter a value for temperature deviation from ISA. After entering the required values, the user may click the "Calculate" button at the lower end of the screen to run the APC session.

The results from APC for a single aircraft session will be similar to what illustrated in Figure B.3, in which the output of the session will be displayed in a spread-sheet-like table format. The first column of the output table is the pressure altitude, in feet, and as the flight selected for the performance calculation is descent, then pressure altitude is listed in descending order starting and ending with the altitudes that the user has defined. The second column of the output represents the aircraft mass, in kilograms. The third and fourth columns lists the aircraft speed in Mach and true airspeed (TAS), in knots, respectively. The fifth column computes the aircraft's rate of descent (ROD) in feet per minute, while the sixth column lists calculations for aircraft's gradient, in degrees. Lastly, the seventh column lists calculations for fuel flow during the descent, in kilograms per second. For the user's convenience, APC plot graphs of the results.

Finally, it is important to mention that the user can convert the units of the calculated parameters by simply specify this selection before initialize the APC session.

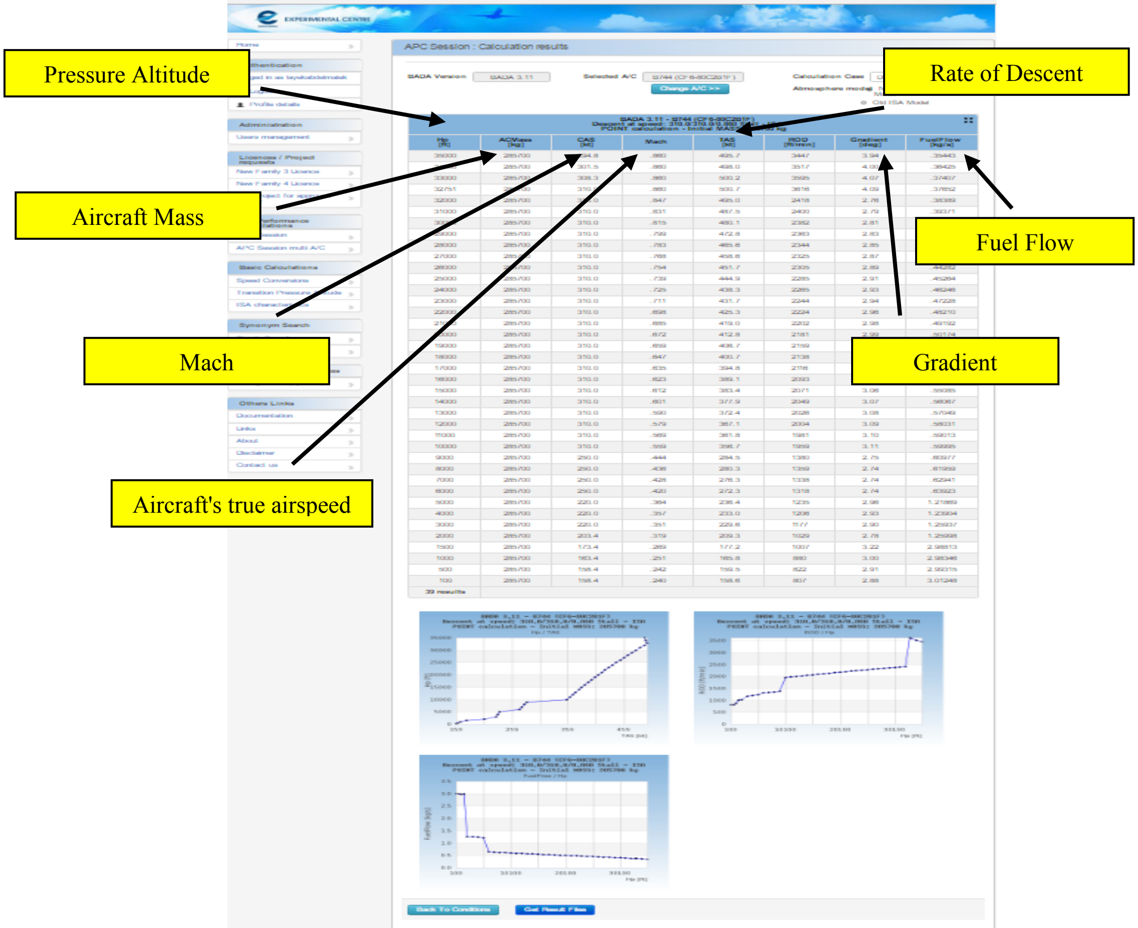

Figure B.3 Output of AP single aircraft session.

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